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ASD-TDR-63-264
PART II

DEVELOPMENT OF LUBRICANT SCREENING TESTS AND EVALUATION OF LUBRICANTS FOR GAS TURBINE ENGINES FOR COMMERCIAL SUPERSONIC TRANSPORT

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-63-264, PART II

May 1965

Air Force Aero Propulsion Laboratory
Research and Technology Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

Project No. 648D

Supersonic Transport Research Program
Sponsored by
The Federal Aviation Agency

(Prepared under Contract No. AF 33(657)-11028 by the Southwest Research Institute, San Antonio, Texas:
B. B. Baber, J. P. Cuellar, P. M. Ku, C. W. Lawler, C. M. Monita, authors.)

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FOREWORD

The work described in this report was performed at Southwest Research Institute, San Antonio, Texas, under USAF Contract 33(657)-11028, Project 648D, and administered by the Fuels and Lubricants Branch, Air Force Aero Propulsion Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The project engineers were Messrs. G. A. Beane and L. J. DeBrohun.

This report covers the work performed in the period of March 1, 1963 through October 31, 1964.

ABSTRACT

Test methods, developed during the first year of this program and described in ASD-TDR-63-264, Part I, were used to evaluate the high-temperature capabilities of candidate lubricants intended for use in the advanced gas turbine engines of the commercial supersonic transport. The candidate lubricants were evaluated in the following tests: (1) lubricant oxidation-corrosion test, (2) lubricant deposits and degradation test, and (3) gear load-carrying capacity test. In addition, preliminary tests were conducted on the 3-ball/cone fatigue tester to determine its operating capabilities and to study the mode of fatigue failures obtained with the tester.

Of the nearly 40 different candidate lubricants evaluated in one or more of the high-temperature tests described, only one lubricant, a 5P4E polyphenyl ether, exhibits adequate performance up to 600°F. However, its high pour point, high viscosity, and significant copper corrosion tendency, along with its high cost, are factors to be considered. Other than the 5P4E polyphenyl ether, and disregarding cost and availability, four other candidates show acceptable performance up to 500°F with no significant metal corrosion, and are therefore considered as most promising for the supersonic transport engine application.

This technical report has been reviewed and is approved.

BLACKWELL C. DUNNAM
Chief, Fuels and Lubricants Branch
Air Force Aero Propulsion Laboratory

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
	A. General Remarks	1
	B. Lubricants Evaluated	2
II.	LUBRICANT OXIDATION-CORROSION	3
	A. General Remarks	3
	B. 18-Hr 425 to 500°F Oxidation-Corrosion Test	4
	C. High-Temperature Oxidation-Corrosion Test	34
	D. CRC Oxidation-Corrosion Tests	62
	E. 10-Hr Modified Oxidation-Corrosion Test	77
	F. Conclusions	80
III.	LUBRICANT DEPOSITS AND DEGRADATION	86
	A. General Remarks	86
	B. Test Equipment	87
	C. Test Procedures and Techniques	87
	D. Test Results and Discussion	89
	E. Conclusions	121
IV.	GEAR LOAD-CARRYING CAPACITY	126
	A. General Remarks	126
	B. Test Equipment and Techniques	127
	C. Test Procedures	128
	D. Test Results and Discussion	128
	E. Calibration of the WADD High-Temperature Gear Machine	149
	F. Conclusions	151
V.	ROLLING-CONTACT FATIGUE	154
	A. General Remarks	154
	B. Apparatus and Techniques	156
	C. Calibration of the Torque Measurement System	159
	D. Preliminary Operation	160
	E. Preliminary Fatigue Testing	164
	F. Conclusions	168

TABLE OF CONTENTS (Cont'd)

		Page
VI.	SUMMARY	170
LIST OF REFERENCES		176
APPENDIX		177

LIST OF ILLUSTRATIONS

Figure		Page
1	Effect of Several Test Variables on 5P4E Lubricant Deterioration	40
2	Effect of Nitrogen-Air Mixtures on 5P4E Lubricant Deterioration at 600°F	42
3	Effect of Nitrogen-Air Mixtures on 5P4E Lubricant Deterioration at 600°F	44
4	Effect of Air Flow rate on Deterioration of Three Oil Types	57
5	Effect of Air Flow Rate on Lubricant Deterioration of O-62-25	58
6	Effect of Air Flow Rate on Lubricant Deterioration of O-64-13	59
7	Effect of Air Flow Rate on Lubricant Deterioration of H-1001	60
8	Effect of Air Flow Rate on Lubricant Deterioration of ATL-401	61
9	Repeatability of CRC Oxidation-Corrosion Test Viscosity Results	71
10	Time-Temperature Plot for CRC Method A Diffuser Tests	73
11	Correlation of Viscosity Results, 10-Hr Modified Oxidation-Corrosion Test vs 16-Hr Bearing Deposit Test Samples	82
12	Overall Deposit Demerit Ratings Obtained for 5P4E under Various Test Conditions	94
13	Percent Viscosity Increase for 5P4E under Various Test Conditions	95
14	Test Bearing Deposit Demerit Ratings for All 5P4E Tests	97

LIST OF ILLUSTRATIONS (Cont'd)

Figure		Page
15	Viscosity Increase of 5P4E Polyphenyl Ether Obtained in 100-mm Bearing Test.	100
16	Viscosity Increase of ATL-305 Obtained in 100-mm Bearing Test	113
17	Induction Heating Control System	130
18	Load-Carrying Capacity Versus Test Gear Temperature using Nitralloy N Steel Test Gears	135
19	Relation between Load-Carrying Capacity Obtained at 165°F and 425°F Test Conditions with Nitralloy N Steel Test Gears	141
20	Effect of Lubricant Flow Rate on Gear Tooth Scuffing at 425°F Test Gear Temperature Conditions. .	146
21	Effect of Lubricant Flow Rate on Gear Tooth Scuffing at 600°F Test Gear Temperature Conditions. .	147
22	Effect of Lubricant Flow Rate on Gear Tooth Scuffing at 425°F Test Gear Temperature Conditions. .	148
23	Relationship between Average Scuff Increase Obtained between 800 and 270 ml/min Test Oil Flow Rate and Load-Carrying Capacity Scatter Obtained with the Respective Lubricants	150
24	Comparison of Static and Dynamic Curves for High Speed Calibration.	152
25	Cross Section of Three-Ball/Cone Fatigue Tester . . .	157
26	Static Calibration of Strain Gage Torque Measurement System of 3-Ball/Cone Fatigue Tester	161
27	Load Versus Calculated Hertz Stress for 3-Ball/Cone Fatigue Tester	162
28	Dynamic Calibration of Strain Gage Torque Measurement System of 3-Ball/Cone Fatigue Tester	163
29	Weibull Plot for Preliminary Tests on 3-Ball/Cone Fatigue Tester	169

LIST OF TABLES

Table		Page
1	Comparison of Results for 18-Hour 425°F Oxidation-Corrosion Tests with Oil Bath and Aluminum Block Test Apparatus	7
2	Summary of 18-Hr Oxidation-Corrosion Test Viscosity Increase Data	10
3	Results of 18-Hour Oxidation-Corrosion Test on ATL-309	11
4	Results of 18-Hour Oxidation-Corrosion Tests on ATL-308	12
5	Results of 18-Hour Oxidation-Corrosion Test on ATL-406	13
6	Results of 18-Hour Oxidation-Corrosion Test on O-62-25	14
7	Results of 18-Hour Oxidation-Corrosion Tests on O-63-26	15
8	Results of 18-Hour Oxidation-Corrosion Tests on H-1001	16
9	Results of 18-Hour Oxidation-Corrosion Tests on O-64-13	17
10	Results of 18-Hour Oxidation-Corrosion Tests on MLO-62-1013 -- Oil Bath Apparatus	18
11	Results of 18-Hour Oxidation-Corrosion Tests on ATL-401	19
12	Results of 18-Hour Oxidation-Corrosion Tests on ATL-305	20
13	Results of 18-Hour Oxidation-Corrosion Tests on ATL-404	21
14	Results of 18-Hour Oxidation-Corrosion Tests on ATL-405	22

LIST OF TABLES (Cont'd)

Table		Page
15	Results of 18-Hour Oxidation-Corrosion Tests on ATL-306	23
16	Results of 18-Hour Oxidation-Corrosion Tests on ATL-402	25
17	Results of 18-Hour Oxidation-Corrosion Tests on ATL-304	26
18	Results of 18-Hour Oxidation-Corrosion Tests on MLO-63-1001 -- Oil Bath Apparatus	27
19	Results of 18-Hour Oxidation-Corrosion Tests on ATL-403	28
20	Results of 18-Hour Oxidation-Corrosion Tests on O-64-17	29
21	Effect of Air Humidity on 425°F 18-Hr Oxidation-Corrosion Test Results	31
22	Effect of Air Humidity on 425°F 18-Hr Oxidation-Corrosion Test Results for Two MIL-L-9236 Type Lubricants	32
23	Effect of Air Humidity on 18-Hour Oxidation-Corrosion Test Results at Various Temperatures	33
24	Summary of Oxidation-Corrosion Test Results on F-1041 at 550°F	36
25	Summary of Oxidation-Corrosion Test Results on F-1041 at 600°F	37
26	Summary of Oxidation-Corrosion Test Results on F-1041 at 650°F	38
27	Effect of Condensate Return on 600°F Oxidation-Corrosion Test Results for F-1041	45
28	Effect of Metals on Oxidation-Corrosion Test Viscosity Results for F-1041	47

LIST OF TABLES (Cont'd)

Table		Page
29	Correlation of Oxidation-Corrosion Test Viscosity Data with Bearing Test Results for F-1041	48
30	Summary of Oxidation-Corrosion Test Results for MLO-62-1005 at 475°F	51
31	Glassware and Oil Sludge Appearance for 475°F Oxidation-Corrosion Test on MLO-62-1005	52
32	Summary of High-Temperature Oxidation-Corrosion Test Results on ATL-307	54
33	Summary of Metal Specimen Weight Changes and Appearances for High-Temperature Oxidation-Corrosion Tests on ATL-307	55
34	Comparison of CRC Oxidation-Corrosion Test Methods	63
35	Summary of Oxidation-Corrosion Test Results on H-1001 at 425°F	67
36	Summary of Oxidation-Corrosion Test Results on ATL-305 at 450°F	68
37	Summary of Oxidation-Corrosion Test Results on ATL-401 at 450°F	69
38	Effect of Air Dispersion on Metal Specimen Corrosion with ATL-305	75
39	Effect of Air Dispersion on Metal Specimen Corrosion with F-1041	76
40	Effect of Air Dispersion on Metal Specimen Corrosion with ATL-401	78
41	Comparison of 10-Hr Modified Oxidation-Corrosion Test Results and Bearing Test Data	81
42	Results of 5P4E Lubricant Deposits and Degradation	91

LIST OF TABLES (Cont'd)

Table		Page
43	Summary of Repeatability Test Results on 5P4E Polyphenyl Ether	98
44	Summary of Lubricant Deposits and Degradation Results on Eleven Candidate Lubricants	101
45	Comparison of Bearing Test Results on Lubricant O-62-25.	104
46	Comparison of Bearing Test Results on Lubricant H-1001	108
47	Comparison of Bearing Test Results on Lubricant ATL-401	118
48	Comparison of Principal Dimensions of Standard Ryder Test Gears with High-Temperature Test Gears.	129
49	Comparison of Load-Carrying Capacity Test Methods	131
50	Summary of Individual Load-Carrying Capacity Determinations Obtained using Nitralloy N Steel Test Gears	133
51	Summary of Average Load-Carrying Capacity Results Obtained using Nitralloy N Steel Test Gears .	134
52	Effect of Oil Deterioration on Load-Carrying Capacity of O-61-20	139
53	Extended Time Test Results Obtained on 5P4E Polyphenyl Ether at 700°F Test Gear Temperature .	143
54	Effect of Lubricant Volume on Load-Carrying Capacity at Gear Temperatures above 500°F.	144
55	Results of Preliminary 3-Ball/Cone Fatigue Tests. . .	166
56	Summary of Test Results on Candidate Lubricants of Potential Interest	171

LIST OF TABLES (Cont'd)

Table		Page
57	Description of Test Lubricants	177
58	Results of 425°F Oxidation-Corrosion Tests on H-1001	178
59	Metal Specimen Weight Change for 425°F Oxidation-Corrosion Tests with H-1001	179
60	Results of 450°F Oxidation-Corrosion Tests on ATL-305	180
61	Metal Specimen Weight Change for 450°F Oxidation-Corrosion Tests with ATL-305	181
62	Results of 450°F Oxidation-Corrosion Tests on ATL-401	182
63	Metal Specimen Weight Change for 450°F Oxidation-Corrosion Tests with ATL-401	183
64	Summary Data on F-1041, Bearing Test No. 16 . . .	184
65	Summary Data on F-1041, Bearing Test No. 17 . . .	185
66	Summary Data on F-1041, Bearing Test No. 18 . . .	186
67	Summary Data on F-1041, Bearing Test No. 20 . . .	187
68	Summary Data on F-1041, Bearing Test No. 21 . . .	188
69	Summary Data on F-1041, Bearing Test No. 22 . . .	189
70	Summary Data on F-1041, Bearing Test No. 23 . . .	190
71	Summary Data on F-1041, Bearing Test No. 24 . . .	191
72	Summary Data on F-1041, Bearing Test No. 25 . . .	192
73	Summary Data on F-1041, Bearing Test No. 26 . . .	193
74	Summary Data on F-1041, Bearing Test No. 27 . . .	194

LIST OF TABLES (Cont'd)

Table		Page
75	Summary Data on F-1041, Bearing Test No. 28	195
76	Summary Data on F-1041, Bearing Test No. 30	196
77	Summary Data on F-1041, Bearing Test No. 31	197
78	Summary Data on F-1041, Bearing Test No. 32	198
79	Summary Data on F-1041, Bearing Test No. 34	199
80	Summary Data on F-1041, Bearing Test No. 35	200
81	Summary Data on F-1041, Bearing Test No. 36	201
82	Summary Data on F-1041, Bearing Test No. 38	202
83	Summary Data on O-62-25, Bearing Test No. 47	203
84	Summary Data on O-62-25, Bearing Test No. 48	204
85	Summary Data on O-62-25, Bearing Test No. 49	205
86	Summary Data on O-62-25, Bearing Test No. 50	206
87	Summary Data on O-62-25, Bearing Test No. 45	207
88	Summary Data on O-62-25, Bearing Test No. 46	208
89	Summary Data on H-1001, Bearing Test No. 76	209
90	Summary Data on H-1001, Bearing Test No. 66	210
91	Summary Data on H-1001, Bearing Test No. 72	211
92	Summary Data on H-1001, Bearing Test No. 51	212
93	Summary Data on H-1001, Bearing Test No. 52	213
94	Summary Data on H-1001, Bearing Test No. 53	214
95	Summary Data on H-1001, Bearing Test No. 54	215
96	Summary Data on H-1001, Bearing Test No. 59	216

LIST OF TABLES (Cont'd)

Table		Page
97	Summary Data on H-1001, Bearing Test No. 60. . . .	217
98	Summary Data on H-1001, Bearing Test No. 61. . . .	218
99	Summary Data on H-1001, Bearing Test No. 62. . . .	219
100	Summary Data on H-1001, Bearing Test No. 63	220
101	Summary Data on H-1001, Bearing Test No. 64. . . .	221
102	Summary Data on H-1001, Bearing Test No. 65. . . .	222
103	Summary Data on H-1001, Bearing Test No. 55. . . .	223
104	Summary Data on O-64-13, Bearing Test No. 77 . . .	224
105	Summary Data on O-64-13, Bearing Test No. 79 . . .	225
106	Summary Data on O-64-13, Bearing Test No. 80 . . .	226
107	Summary Data on O-64-17, Bearing Test No. 88 . . .	227
108	Summary Data on ATL-304, Bearing Test No. 39 . . .	228
109	Summary Data on ATL-305, Bearing Test No. 44 . . .	229
110	Summary Data on ATL-305, Bearing Test No. 43 . . .	230
111	Summary Data on ATL-305, Bearing Test No. 42 . . .	231
112	Summary Data on ATL-307, Bearing Test No. 41 . .	232
113	Summary Data on ATL-307, Bearing Test No. 40 . .	233
114	Summary Data on ATL-401, Bearing Test No. 70 . .	234
115	Summary Data on ATL-401, Bearing Test No. 58 . .	235
116	Summary Data on ATL-401, Bearing Test No. 78 . .	236
117	Summary Data on ATL-401, Bearing Test No. 56 . .	237

LIST OF TABLES (Cont'd)

Table		Page
118	Summary Data on ATL-401, Bearing Test No. 73	238
119	Summary Data on ATL-401, Bearing Test No. 71	239
120	Summary Data on ATL-402, Bearing Test No. 67	240
121	Summary Data on ATL-402, Bearing Test No. 68	241
122	Summary Data on ATL-403, Bearing Test No. 69	242
123	Summary Data on ATL-405, Bearing Test No. 75	243
124	Summary Data on ATL-405, Bearing Test No. 74	244

I. INTRODUCTION

A. General Remarks

This report summarizes the work performed at Southwest Research Institute during the period of March 1, 1963 through October 31, 1964, on a program concerned with the development of lubricant screening tests and the evaluation of lubricants for advanced gas turbine engines for the commercial supersonic transport, under Contract AF 33(657)-11028, Project 648D. The present program represents a continuation of work initiated on May 1, 1962, as a part of a broad program of research and study to investigate the technical and economic problems related to the commercial supersonic transport being conducted with the financial support of the Federal Aviation Agency, Washington, D.C. Technical administration of this program was provided by the Fuels and Lubricants Branch, Air Force Aero Propulsion Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with the National Aeronautics and Space Administration lending basic research and technical support as needed.

A discussion of the basic concepts of this program has been presented previously[(1)*] and will not be repeated here. It is believed that from the experience gained in the lubricant screening tests employed for the past and current versions of aviation gas turbine lubricants, such as those employed in Military Specifications MIL-L-7808 and MIL-L-9236, the high-temperature lubricant performance characteristics could be defined within reasonable confidence by the following basic tests:

(1) Lubricant oxidation-corrosion test

(2) Lubricant deposits and degradation test

(3) Gear load-carrying capacity test

(4) Rolling-contact fatigue test

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*Superscript numbers in parentheses refer to the List of References.

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Test equipment and procedures were developed for all four of the above-mentioned tests. Evaluations of candidate lubricants were limited, however, to various high-temperature test conditions of the first three tests listed.

B. Lubricants Evaluated

A total of 63 lubricants were evaluated in one or more of the high-temperature tests during the course of the program. Not all of these lubricants were considered to be "candidate lubricants," but were included in the various phases of the program primarily to aid test method development. In addition, some of these lubricants represented different batches of the same nominal formulation and should not be considered as entirely different lubricants or types of lubricants.

Table 57 in the Appendix presents a listing of the lubricants employed in the portion of the program covered by this report, together with the pertinent available information on each lubricant.

II. LUBRICANT OXIDATION-CORROSION

A. General Remarks

The objectives of the lubricant oxidation-corrosion phase were to develop apparatus and procedures for determining the oxidation and corrosion characteristics of high-temperature gas turbine lubricants and to evaluate the oxidation and corrosion characteristics of candidate lubricants under environmental conditions representative of Mach 2.5 to 3 class gas turbine engine designs.

In accomplishing the above objectives, two separate but related test procedures have been utilized. Studies in the 425 to 500° F region generally employed an 18-hr oxidation-corrosion test procedure[1] developed previously for evaluation of lubricants at 425° F. For that work, an oil bath with a maximum temperature capability of 500° F was considered adequate. The current program for supersonic transport engine application, however, necessitated the use of a test apparatus with a higher temperature capability. Consequently, a high-temperature oxidation-corrosion test apparatus using an aluminum heating block, having a temperature capability exceeding 800° F, was designed and constructed.[1] In the early stages of this effort, a study was conducted which indicated that excellent correspondence of results existed between data obtained in the oil bath apparatus and the aluminum block apparatus under equivalent test conditions.[1] Therefore, the work during the present contract was conducted almost exclusively by use of the aluminum block apparatus.

Using the 18-hr procedure, over a temperature range of 425 to 500° F, oxidation-corrosion studies were carried out on 18 advanced lubricant candidates. In addition, several lubricants were subjected to 18-hr runs to examine the effect of air humidity. The normal test procedure employs clean, dry air; however, there is increasing interest in the use of humidified air for oxidation-corrosion test evaluations. The moist air condition is believed to be more realistic in relation to other lubricant screening tests, in particular the bearing deposits test which employs air nominally water-saturated.

A major objective of this phase was an evaluation of the oxidation-corrosion characteristics of a mixed isomer 5P4E polyphenyl ether over a temperature range of 550 to 650° F. This effort provided for the establishment of the baseline performance of this fluid for comparison with the performance of high-temperature lubricant candidates. The results contained herein are intended to supplement 5P4E test data presented in Part I[1] of this report.

Aside from temperature, probably the most significant factor affecting lubricant performance in any oxidation-corrosion test is oxygen availability, i.e., test air flow rate. This variable was, therefore, a major item of study in this work. Several lubricants selected by RTD were examined in test series conducted over an air flow range of 5 to 130 liters/hr. The fluids selected included not only those of interest for high-temperature application, but also some lubricants capable of only moderate temperature (425°F) environments.

Extensive testing was accomplished on three lubricants using two oxidation-corrosion test procedures under consideration by the Bench Tests Panel of the Coordinating Research Council. At the request of RTD, this work was conducted to assist the Panel in its development of a suitable oxidation-corrosion test procedure. The Panel's objective is to formulate a 500°F test for evaluation of advanced turbine lubricants. In initial discussions, unanimous agreement was not obtained among the Panel members on the philosophy of the procedure. Consequently, it was decided to evaluate and compare two alternative procedures: Method A - a low air flow, reflux test, and Method B - a high air flow, nonreflux test. It is expected that selection of a final procedure will be made after extensive investigation of the two tentative methods. It is more probable, however, that the ultimate criteria for selection will be high-temperature engine test data.

At a recent meeting, the Bench Tests Panel requested a program on the effect of air dispersion on oxidation-corrosion test results. This question was raised chiefly in regard to metal specimen corrosion. It was felt that the normal open-end air tube might not provide uniform air-to-metal contact and might thus be misleading in defining the metal corrosion properties of a lubricant. In addition, it was conjectured that some improvement in test repeatability might be obtained by the use of highly dispersed air. It was therefore decided to investigate the advantages and disadvantages of employing fritted-glass air tubes with the CRC test procedures.

Some preliminary results were also obtained using a modified oxidation-corrosion test procedure in an attempt to formulate a procedure which would provide correlation with lubricant viscosity data from the 100-mm bearing deposit test. A total of six lubricants were evaluated in this study. Satisfactory correlation was obtained for four of these oils, but very unsatisfactory correlation was evident in two cases.

B. 18-Hr 425 to 500°F Oxidation-Corrosion Test

1. Apparatus and Test Procedure

An 18-hr oxidation-corrosion test procedure and apparatus, previously described in detail[1], was used in this area of investigation.

Aside from temperature, probably the most significant factor affecting lubricant performance in any oxidation-corrosion test is oxygen availability, i.e., test air flow rate. This variable was, therefore, a major item of study in this work. Several lubricants selected by RTD were examined in test series conducted over an air flow range of 5 to 130 liters/hr. The fluids selected included not only those of interest for high-temperature application, but also some lubricants capable of only moderate temperature (425°F) environments.

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B. 18-Hr 425 to 500°F Oxidation-Corrosion Test

1. Apparatus and Test Procedure

An 18-hr oxidation-corrosion test procedure and apparatus, previously described in detail[1], was used in this area of investigation.

This procedure was originally developed by SwRI to provide reasonable correlation with 425°F engine tests conducted by RTD. The objective of the work described here was to determine the lubricants' temperature breakpoints with respect to oxidation stability by increasing the test temperature from an initial value of 425°F, in 25°F increments, until a sample viscosity increase at 100°F of 100 percent or more was obtained.

The 18-hr test was originally formulated using a stirred, thermostated oil bath as the heating medium. Briefly, the conditions were 18-hr duration, 425°F bath temperature, 197 liters/hr air flow rate, 350-ml sample, and a five-metal corrosion specimen set consisting of aluminum, titanium, silver, mild steel, and stainless steel. The test glassware employed a 64-mm Pyrex sample tube with a nonreflux configuration, i.e., condensed oil and vapors were not returned to the sample tube but were directed to a separate overboard collection system.

The aluminum block apparatus was constructed for use with a 51-mm Pyrex sample tube. The glassware configuration and metal specimens are otherwise similar to those of the oil bath apparatus. Because of the smaller tube diameter, equivalent 18-hr test conditions in the block require a 200-ml sample with 130 liters/hr air flow rate. One other major difference between the two apparatus lies in the test temperature reference point. All runs in the block were conducted by maintaining the lubricant sample at the specified test temperature, whereas oil-bath tests were performed by controlling the heat medium fluid. Thus, a 425°F test in the latter unit resulted in a sample lubricant temperature of approximately 422 to 423°F. The effect of this slight temperature difference on oxidation-corrosion test results is illustrated in the succeeding section.

2. Test Results and Discussion

a. Correspondence of Results between Oil Bath and Aluminum Block Test Apparatus

As noted previously, the oxidation-corrosion test apparatus with the oil bath was normally used in the temperature range of 425 to 500°F, while the high-temperature oxidation-corrosion test apparatus with the aluminum heating block was originally used at temperatures of 500°F and above. Although the two test devices are similar in operating principles and basic configurations, there are, nevertheless, significant differences in design details. These differences in design details resulted mainly from the fact that the high-temperature apparatus incorporated refinements suggested by experience.

It is clearly desirable, in order to establish the confidence of both types of test apparatus, to examine whether or not a correlation exists between the results obtained from the two test apparatus, under comparable test conditions. It would have been desirable to perform such comparative tests over the entire overlapping temperature range of the two apparatus. However, owing to the very limited number of suitable lubricants available, it was decided to conduct the tests only at 425°F, using three MIL-L-9236 type lubricants (O-60-23, O-60-27, and O-59-26) for which data from the standard 18-hr 425°F test (using the oil bath apparatus) were available.

Table 1 compares the results from three different series of tests on the three oils, all conducted in accordance with the standard 18-hr 425°F test procedure, using five metal specimens (Al, Ti, Ag, mild steel, and stainless steel), and without condensate return. The test conditions were as follows:

	A. Bath	B. Bath	C. Block
Sample temperature, °F	422-423	425	425
Heat medium temperature, °F	425	428	426
Air rate, liters/hr	197	197	130
Sample volume, ml	350	350	200

It will be noted that the Series A tests were conducted using the standard 18-hr 425°F test conditions developed for the oil bath type apparatus. In these tests, following the usual practice of lubricant testing, the oil bath temperature was controlled at 425°F, which gave a test lubricant sample temperature of 422 to 423°F. These results were obtained previously[1] and are included in Table 1 only for the purpose of comparison.

The Series B tests were performed under otherwise identical conditions as the Series A tests, except that the oil bath temperature was increased to 428°F so as to give a test lubricant sample temperature of 425°F. This series was run in order to provide a basis for direct comparison of its results with those obtained from the Series C tests, for which the test lubricant sample temperature was controlled at 425°F.

The Series C tests were conducted using the high-temperature test apparatus with the test lubricant sample temperature controlled at 425°F. As noted previously, the temperature of the test lubricant in the sample tube is generally lower than the heat medium (whether oil bath or aluminum block) temperature; and this temperature difference varies significantly with the temperature level of the test. Consequently, in all tests performed in the high-temperature apparatus, the test lubricant sample temperature, rather than the heat medium temperature, has been controlled at

TABLE 1. COMPARISON OF RESULTS FOR 18-HOUR 425° F OXIDATION-CORROSION TESTS WITH OIL BATH AND ALUMINUM BLOCK TEST APPARATUS

Oil Code:	O-60-23			O-60-27			O-59-26		
Heat Medium:	A. Bath	B. Bath	C. Block	A. Bath	B. Bath	C. Block	A. Bath	B. Bath	C. Block
Vis, cs at 100° F									
Initial	16.0	16.0	16.0	15.0	15.0	15.0	18.7	18.7	18.7
Final	23.8	26.4	26.7	19.4	35.6	34.6	41.5	55.0	59.3
% Increase	48.8	65.0	66.9	29.3	137	131	122	194	217
NN, mg KOH/g									
Initial	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Final	4.7	6.0	6.2	0.8	7.8	9.3	6.8	9.8	10.7
Overhead product									
Weight, g	-	90	46	-	169	89	-	80	42
Vis, cs at 100° F	-	13.2	12.8	-	11.5	11.2	-	10.3	10.1
NN, mg KOH/g	20.9	22.3	31.0	2.0	11.6	14.9	55.7	59.0	74.3
Oil loss									
Weight, g	86	97	50	144	173	92	74	92	52
Volume, ml	90	101	52	149	179	95	78	97	55
Percent	26	29	26	43	51	48	22	28	28

	A. Bath	B. Bath	C. Block
Sample temperature, °F	422-423	425	425
Heat medium temperature, °F	425	428	426
Air rate, liters/hr	197	197	130
Sample volume, ml	350	350	200
Condensate return	No	No	No
Metal specimens	Al, Ti, Ag, steel, stainless steel, all tests		

All results are averages of two or more determinations.

the desired value, because the sample temperature is considered to be the more significant parameter in describing lubricant performance. The Series C tests employed an air flow rate of 130 liters/hr and a sample volume of 200 ml, as compared with 197 liters/hr and 350 ml for the Series A and Series B tests. These changes were made to account for the different sample tube sizes used, which were 64-min O.D. in the oil bath type apparatus and 51-mm O.D. in the aluminum block type apparatus. An air flow rate of 130 liters/hr was established for the small sample tube so as to give the same air velocity in the tube as that given by an air flow rate of 197 liters/hr in the large sample tube. Further, the ratio of air flow rate to test lubricant sample volume also was approximately comparable for the two cases.

As seen in Table 1, the effect of a 2 to 3°F increase in sample temperature in the tests using the oil bath apparatus was quite pronounced, particularly for O-60-27 which gave approximately a twofold increase in final sample viscosity and a tenfold increase in final sample neutralization number. The viscosity and neutralization number of the overhead product reflected a similar increase. Likewise, the oil loss, both in terms of weight and as a percent of the initial sample weight, was increased.

Table 1 also shows that when the sample temperature was maintained constant at 425°F, the tests using the oil bath apparatus and the aluminum block apparatus gave comparable final sample viscosity and final sample neutralization number. Further, although the weight of oil loss was less for the block test than for the bath test, the percent oil loss based on the initial sample weight was comparable for the two cases. Referring to the overhead product, Table 1 shows that the block test gave somewhat lower viscosity but significantly higher neutralization number than the bath test. The reason for this anomaly is not apparent; however, considering the results as a whole, it may be said that the two tests gave excellent correspondence of data on the performance of the test lubricant, including final sample viscosity, final sample neutralization number, and percent of oil loss.

In view of the excellent correspondence of data obtained with the two test apparatus when the test lubricant sample temperature was controlled and the air flow rate adjusted to give the same air velocity in the sample tubes, RTD directed that all subsequent work in the 425 to 500°F temperature range be conducted in the high-temperature aluminum block test apparatus.

b. Lubricant Screening Tests

Using the standard 18-hr oxidation-corrosion test procedure, tests were performed on 18 experimental lubricants selected by RTD.

The objective of this work was to determine the maximum temperature capability of the fluids as indicated by sample viscosity increase. A viscosity increase of 100 percent or more at any test temperature was considered unsatisfactory and cause for elimination of the lubricant from tests at the next higher temperature.

Using this performance basis, Table 2 summarizes the temperature capability of the 18 lubricants examined with the 18-hr test procedure. The lubricants are generally listed according to increasing performance rank. Six lubricants failed the 18-hr test at 425° F. Detailed test results for these runs are shown in Tables 3 to 8. As illustrated in Table 4, test data at 450° F were also obtained on ATL-308 even though its performance at 425° F was unsatisfactory. This apparent procedural contradiction occurred because the lubricant was initially run at the higher temperature in order to accommodate the oil in a test sequence under way at the time the sample was received. It will also be noted that two 425° F tests were conducted with ATL-308. In addition to the standard 18-hr test, RTD requested a departure from the normal procedure and the lubricant was subsequently retested at 425° F under identical conditions but using a condensate return apparatus. The data were quite comparable in both cases except for sample viscosity increase. The reflux condition significantly lowered the final sample viscosity, although the 177 percent increase was still above that considered satisfactory.

Lubricants O-63-26 and H-1001 also failed the 18-hr test at 425° F with a viscosity increase at or near 100 percent. Because these performances might be considered marginal, however, O-63-26 and H-1001 were examined at 450° F. At the higher test temperature both oils (Tables 7 and 8) exhibited relatively extreme increases in viscosity and neutralization number although there was no instance of significant metal corrosion specimen attack.

Seven lubricants evaluated in this program indicated a satisfactory performance at 425° F but failed at 450° F. Detailed test results are presented in Tables 9 to 15 for these oils. It will be noted that MLO-62-1013 was one of two oils evaluated in the oil bath apparatus. Thus, these runs were performed at a sample temperature approximately 2 to 3° F below the stated test temperature. Had the lubricant been run in the aluminum block apparatus, it is expected that sample deterioration would have been slightly higher. However, it is probable that the relative performance of MLO-62-1013 would not have been appreciably altered.

Of the seven lubricants which exhibited failure at 450° F in the 18-hr test, ATL-306 demonstrated the more superior performance. The fluid showed very good oxidation stability at 425° F with a 100° F viscosity

TABLE 2. SUMMARY OF 18-HR OXIDATION-CORROSION TEST VISCOSITY INCREASE DATA

Lubricant Code	Percent 100°F Viscosity Increase for Test at 425°F	450°F	475°F	500°F
ATL-309	>25,000			
ATL-308	745	Gelled		
ATL-406	416			
O-62-25	151			
O-63-26	118[a]	1790		
H-1001	100	1845		
O-64-13	68	2861		
MLO-62-1013	59[b]	1150[b]		
ATL-401	41	346		
ATL-305	45	296		
ATL-404	14	281		
ATL-405	11	259		
ATL-306	12	104		
ATL-402	42	86	403	
ATL-304	39	82	394	
MLO-63-1001	38[b]	79[b]	340[b]	
ATL-403	15	29	60	437
O-64-17	14	26	53	392

(a) Average of duplicate tests.

(b) Test run in oil bath apparatus. Sample temperature approximately 2-3°F below that listed.

TABLE 3. RESULTS OF 18-HOUR OXIDATION-CORROSION TEST ON ATL-309

Sample temperature, °F		425
Viscosity at 100°F, cs:	Initial	43.07
	Final	>13,000
	% Increase	>25,000
Viscosity at 210°F, cs:	Initial	6.01
	Final	111.0
	% Increase	1,750
Neut. no., mg KOH/g:	Initial	0.11
	Final	14.02
Overhead product neut. no., mg KOH/g		22.2
Overhead product collected, g		70.
Oil loss, wt %		47
Metal weight change, mg/cm^2:	Al	+0.07
	Ti	-0.02
	Ag	+0.05
	Steel	+0.13
	SS	+0.05

TABLE 4. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON ATL-308

Sample temperature, °F		425	425(a)	450
Viscosity at 100°F, cs:	Initial	48.95	48.95	48.95
	Final	404.0	135.7	(b)
	% Increase	725	177	-
Viscosity at 210°F, cs:	Initial	7.86	7.86	7.86
	Final	29.51	14.39	1,332
	% Increase	275	83	16,850
Neut. no., mg KOH/g:	Initial	0.38	0.38	0.38
	Final	9.22	8.32	11.97
Overhead product neut. no., mg KOH/g		29.0	-	18.63
Overhead product collected, g		69	-	95
Oil loss, wt %		41	15	59
Metal weight change, mg/cm^2:	Al	0.0	0.0	0.0
	Ti	+0.07	+0.02	-0.05
	Ag	-0.05	-0.09	-0.05
	Steel	+0.04	0.0	0.0
	SS	-0.04	-0.04	+0.07

(a) With condensate return.

(b) Sample semisolid at room temperature.

TABLE 5. RESULTS OF 18-HOUR OXIDATION-CORROSION TEST ON ATL-406

Sample temperature, °F		425
Viscosity at 100°F, cs:	Initial	26.92
	Final	138.9
	% Increase	416
Viscosity at 210°F, cs:	Initial	5.21
	Final	14.25
	% Increase	174
Neut. no., mg KOH/g:	Initial	0.03
	Final	14.13
Overhead product neut. no., mg KOH/g		71.3
Overhead product collected, g		45
Oil loss, wt %		30
Metal weight change, mg/cm^2:	Al	-0.02
	Ti	-0.02
	Ag	-0.12
	Steel	+0.04
	SS	+0.04

TABLE 6. RESULTS OF 18-HOUR OXIDATION-CORROSION TEST ON O-62-25

Sample temperature, °F		425
Viscosity at 100°F, cs:	Initial	15.59
	Final	39.12
	% Increase	151
Viscosity at 210°F, cs:	Initial	3.51
	Final	6.25
	% Increase	78
Neut. no., mg KOH/g:	Initial	0.06
	Final	7.89
Overhead product neut. no., mg KOH/g		28.3
Overhead product collected, g		76
Oil loss, wt %		82
Metal weight change, mg/cm^2:	Al	0.0
	Ti	+0.05
	Ag	-0.20
	Steel	-0.11
	SS	-0.11

TABLE 7. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON O-63-26

Sample temperature, °F		425[a]	450
Viscosity at 100°F, cs:	Initial	27.60	27.60
	Final	60.10	521.5
	% Increase	118	1790
Viscosity at 210°F, cs:	Initial	5.04	5.04
	Final	8.14	31.62
	% Increase	62	527
Neut. no., mg KOH/g:	Initial	0.08	0.08
	Final	6.81	12.93
Overhead product neut. no., mg KOH/g		59.8	88.9
Overhead product collected, g		32	79
Oil loss, wt %		20	50
Metal weight change, mg/cm^2:	Al	-0.02	+0.04
	Ti	-0.03	+0.02
	Ag	-0.04	-0.07
	Steel	+0.04	0.0
	SS	0.0	-0.05

(a) Results are averages of duplicate tests.

TABLE 8. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON H-1001

Sample temperature, °F		425	450
Viscosity at 100°F, cs:	Initial	27.50	27.50
	Final	55.02	534.6
	% Increase	100	1845
Viscosity at 210°F, cs:	Initial	5.08	5.08
	Final	7.69	32.17
	% Increase	51	533
Neut. no., mg KOH/g:	Initial	0.07	0.07
	Final	5.84	9.60
Overhead product neut. no., mg KOH/g		52.6	89.5
Overhead product collected, g		31	81
Oil loss, wt %		20	49
Metal weight change, mg/cm^2:	Al	-0.05	+0.07
	Ti	-0.05	+0.05
	Ag	-0.05	-0.16
	Steel	+0.07	+0.02
	SS	0.0	+0.04

TABLE 9. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON O-64-13

Sample temperature, °F		425	450
Viscosity at 100°F, cs:	Initial	28.43	28.43
	Final	47.90	841.9
	% Increase	68	2861
Viscosity at 210°F, cs:	Initial	5.32	5.32
	Final	7.33	43.41
	% Increase	38	716
Neut. no., mg KOH/g:	Initial	0.28	0.28
	Final	5.39	13.56
Overhead product neut. no., mg KOH/g		30.6	87.2
Overhead product collected, g		41	102
Oil loss, wt %		23	58
Metal weight change, mg/cm^2:	Al	0.0	-0.06
	Ti	-0.04	-0.08
	Ag	-0.08	-0.14
	Steel	+0.04	+0.08
	SS	0.0	-0.02

TABLE 10. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON MLO-62-1013--OIL BATH APPARATUS

Bath temperature, °F		425	450
Viscosity at 100°F, cs:	Initial	28.25	28.25
	Final	44.97	353.0
	% Increase	59	1150
Neut. no., mg KOH/g:	Initial	0.07	0.07
	Final	5.49	8.25
Overhead product neut. no., mg KOH/g		57.8	95.5
Overhead product collected, g		46	123
Oil loss, wt %		33	74
Metal weight change, mg/cm^2:	Al	-0.02	+0.02
	Ti	+0.01	-0.02
	Ag	-0.02	-0.15
	Steel	+0.03	+0.02
	SS	+0.01	+0.01

TABLE 11. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON ATL-401

Sample temperature, °F		425	450
Viscosity at 100°F, cs:	Initial	26.30	26.30
	Final	36.99	117.41
	% Increase	41	346
Viscosity at 210°F, cs:	Initial	5.13	5.13
	Final	6.34	13.45
	% Increase	24	162
Neut. no., mg KOH/g:	Initial	0.11	0.11
	Final	1.48	10.77
Overhead product neut. no., mg KOH/g		25.5	55.4
Overhead product collected, g		22	61
Oil loss, wt %		18	46
Metal weight change, mg/cm^2:	Al	0.0	+0.13
	Ti	-0.05	+0.16
	Ag	0.0	-0.04
	Steel	-0.02	-0.11
	SS	-0.13	0.0

TABLE 12. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON ATL-305

Sample temperature, °F		425	450
Viscosity at 100°F, cs:	Initial	26.16	26.16
	Final	37.99	103.6
	% Increase	45	296
Neut. no., mg KOH/g:	Initial	0.09	0.09
	Final	1.98	9.36
Overhead product neut. no., mg KOH/g		30.9	47.8
Overhead product collected, g		22	61
Oil loss, wt %		17	42
Metal weight change, mg/cm^2:	Al	0.0	-0.05
	Ti	+0.04	-0.05
	Ag	-0.07	-0.04
	Steel	+0.04	+0.05
	SS	-0.02	+0.02

TABLE 13. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON ATL-404

Sample temperature, °F		425	450
Viscosity at 100°F, cs:	Initial	29.60	29.60
	Final	33.79	112.9
	% Increase	14	281
Viscosity at 210°F, cs:	Initial	5.38	5.38
	Final	6.13	12.78
	% Increase	14	138
Neut. no., mg KOH/g:	Initial	0.08	0.08
	Final	0.40	8.05
Overhead product neut. no., mg KOH/g		3.52	46.9
Overhead product collected, g		26	58
Oil loss, wt %		15	34
Metal weight change, mg/cm^2:	Al	0.0	0.0
	Ti	0.0	0.0
	Ag	0.0	+0.10
	Steel	0.0	0.0
	SS	0.0	0.0

TABLE 14. RESULTS OF 18 HOUR OXIDATION-CORROSION TESTS ON ATL-405

Sample temperature, °F		425	450
Viscosity at 100°F, cs:	Initial	34.45	34.45
	Final	38.13	123.6
	% Increase	11	259
Viscosity at 210°F, cs:	Initial	6.31	6.31
	Final	6.78	13.71
	% Increase	7	117
Neut. no., mg KOH/g:	Initial	0.09	0.09
	Final	0.47	8.54
Overhead product neut. no., mg KOH/g		3.98	43.7
Overhead product collected, g		26	60
Oil loss, wt %		16	36
Metal weight change, mg/cm^2:	Al	-0.02	-0.06
	Ti	-0.06	-0.04
	Ag	-0.10	+0.04
	Steel	-0.04	0.0
	SS	0.0	-0.04

TABLE 15. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON ATL-306

Sample temperature, °F		425	450
Viscosity at 100°F, cs:	Initial	27.51	27.51
	Final	30.69[a]	56.14[b]
	% Increase	12	104
Neut. no., mg KOH/g:	Initial	0.29	0.29
	Final	0.29	5.59
Overhead product neut. no., mg KOH/g		15.23	66.1
Overhead product collected, g		7	27
Oil loss, wt %		7	21
Metal weight change, mg/cm^2:	Al	0.0	+0.07
	Ti	+0.07	-0.02
	Ag	-0.05	+0.09
	Steel	+0.04	+0.05
	SS	-0.04	+0.09

(a) Sample contained 0.8 g sludge by 200-mesh screen filtration.

(b) Sample contained 3.0 g sludge by 200-mesh screen filtration.

increase of 12 percent and no change in neutralization number (Table 15). However, measurable sludge weights were obtained by 200-mesh screen filtration of the ATL-306 bulk sample from the 425°F test, and also the subsequent 450°F test. A viscosity increase of 104 percent at the latter temperature was marginal and might have warranted evaluation at 475°F. However, the limited supply of this material precluded further testing.

Three lubricants demonstrated a satisfactory performance at 450°F and subsequent failure at 475°F. Detailed test results are shown in Tables 16 to 18. MLO-63-1001 was tested in the oil bath; however, once again, this factor is not considered of significant importance in affecting the lubricant's rating.

Only two fluids, ATL-403 and O-64-17, merited evaluation at 500°F; however, neither lubricant was satisfactory at this temperature. As shown in Tables 19 and 20, test data for these oils were quite similar in all aspects. Both lubricants contained slight amounts of suspended sludge after each test except the 500°F run with O-64-17. This may have been due to a solubility effect at the higher test temperature.

c. Effect of Air Humidity

Several experiments were conducted to examine the effect of air humidity on 18-hr oxidation-corrosion test results. The normal procedure requires the use of clean, predried air - following the usual practice of oxidation-corrosion test evaluation. There are, however, legitimate objections to the use of dry air in a bench test designed to screen lubricants prior to evaluation in a bearing rig, which normally employs moisture-saturated air, or an engine operated with atmospheric air. Therefore, 18-hr oxidation-corrosion tests were run on several oils using air nominally water-saturated. Air was metered through a 1-in. diffuser stone submerged in distilled water. Air flow from the vapor space of the water saturator was passed through a column of glass wool to remove entrained water droplets, and thence to a flowmeter prior to entering the sample tube. Measurements were made to determine the actual water content of the air at typical flow conditions. A small portion of the total air flow through the water saturator was metered through a preweighed drying tube containing anhydrous calcium sulfate. The weight difference obtained corresponded to a relative humidity of 86 percent, based on the temperature within the saturator (70°F). It should be noted that the saturator temperature, although subject to variations in ambient temperature, remained approximately 8°F below ambient.

A similar attempt to measure the water content of the predried air used in this work gave a relative humidity of less that 0.003

TABLE 16. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON ATL-402

Sample temperature, °F		425	450	475
Viscosity at 100°F, cs:	Initial	46.84	46.84	46.84
	Final	66.40	87.15	235.7
	% Increase	42	86	403
Viscosity at 210°F, cs:	Initial	8.25	8.25	8.25
	Final	10.19	12.22	23.79
	% Increase	24	48	188
Neut. no., mg KOH/g:	Initial	0.12	0.12	0.12
	Final	1.73	3.57	7.77
Overhead product neut. no., mg KOH/g		14.85	19.27	30.5
Overhead product collected, g		18	34	61
Oil loss, wt %		13	23	38
Metal weight change, mg/cm^2:	Al	+0.06	0.0	+0.06
	Ti	-0.02	+0.08	+0.12
	Ag	-0.02	-0.14	+0.10
	Steel	+0.02	-0.08	+0.08
	SS	-0.02	+0.12	-0.04

TABLE 17. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON ATL-304

Sample temperature, °F		425	450	475
Viscosity at 100°F, cs:	Initial	47.11	47.11	47.11
	Final	65.68	85.58	232.6
	% Increase	39	82	394
Neut. no., mg KOH/g:	Initial	0.12	0.12	0.12
	Final	1.84	3.88	8.31
Overhead product neut. no., mg KOH/g		20.9	30.6	30.6
Overhead product collected, g		12	27	52
Oil loss, wt %		13	20	39
Metal weight change, mg/cm^2:	Al	+0.04	0.0	-0.02
	Ti	-0.05	0.0	-0.02
	Ag	0.0	-0.13	-0.09
	Steel	-0.07	-0.07	+0.04
	SS	-0.09	-0.09	+0.02

TABLE 18. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON MLO-63-1001--OIL BATH APPARATUS

		425	450	475
Bath temperature, °F		425	450	475
Viscosity at 100°F, cs:	Initial	46.75	46.75	46.75
	Final	64.69	83.85	205.6
	% Increase	38	79	340
Neut. no., mg KOH/g:	Initial	0.13	0.13	0.13
	Final	1.81	3.81	8.15
Overhead product neut. no. mg KOH/g		16.35	21.0	33.5
Overhead product collected, g		30	60	104
Oil loss, wt %		20	35	61
Metal weight change, mg/cm^2:	Al	+0.01	+0.02	-0.02
	Ti	0.0	+0.02	-0.02
	Ag	-0.01	+0.02	-0.03
	Steel	+0.02	+0.05	+0.04
	SS	+0.21	+0.01	+0.01

TABLE 19. RESULTS OF 18-HOUR OXIDATION-CORROSION TEST ON ATL-403

Sample temperature, °F		425	450	475	500
Viscosity at 100°F, cs:	Initial	27.82	27.82	27.82	27.82
	Final	32.01	35.87	44.65	149.5
	% Increase	15[a]	29[b]	60[b]	437[b]
Viscosity at 210°F, cs:	Initial	5.18	5.18	5.18	5.18
	Final	5.73	6.21	7.20	16.08
	% Increase	11	20	39	210
Neut. no., mg KOH/g:	Initial	0.29	0.29	0.29	0.29
	Final	0.29	0.35	0.25	1.35
Overhead product neut. no., mg KOH/g		10.10	9.57	10.85	24.0
Overhead product collected, g		17	43	74	119
Oil loss, wt %		14	26	42	68
Metal weight change, mg/cm^2	Al	-0.04	-0.02	+0.10	0.0
	Ti	+0.08	0.0	+0.12	-0.04
	Ag	-0.10	-0.20	-0.04	-0.06
	Steel	+0.04	0.0	+0.12	+0.02
	SS	+0.06	+0.14	0.0	-0.06

(a) Sample contained approximately 0.05 ml sludge per 25 ml, obtained by centrifuging.

(b) Sample contained a trace amount of sludge, obtained by centrifuging.

TABLE 20. RESULTS OF 18-HOUR OXIDATION-CORROSION TESTS ON O-64-17

Sample temperature, °F		425	450	475	500
Viscosity at 100°F, cs:	Initial	28.37	28.37	28.37	28.37
	Final	32.38	35.70	43.52	139.52
	% Increase	14[a]	26[a]	53[a]	392
Viscosity at 210°F, cs:	Initial	5.29	5.29	5.29	5.29
	Final	5.81	6.21	7.14	18.11
	% Increase	10	17	35	253
Neut. no., mg KOH/g:	Initial	0.33	0.33	0.33	0.33
	Final	0.24	0.25	0.31	1.72
Overhead product neut. no., mg KOH/g		9.18	9.94	12.78	25.8
Overhead product collected, g		17	38	69	114
Oil loss, wt %		12	22	39	68
Metal weight change, mg/cm^2:	Al	+0.04	+0.10	0.0	0.0
	Ti	-0.10	-0.04	-0.04	-0.06
	Ag	-0.04	-0.12	-0.16	-0.08
	Steel	+0.01	+0.02	-0.06	-0.08
	SS	0.0	0.0	-0.04	+0.02

(a) Sample contained a trace amount of sludge, obtained by centrifuging.

percent (a weight change of less than 0.5 mg for a total air volume of 600 liters).

The results obtained on the effect of humidity using the 18-hr test procedure at 425°F are summarized in Table 21. The lubricants listed are all MIL-L-9236 type formulations which were used in previous work on this phase. The use of moist air resulted in improved performance with respect to viscosity and acidity increases for all oils which had undergone significant deterioration using dry air. In one case, this improved performance was not reflected by neutralization number: O-58-24 showed reduced sample viscosity increase, but a slight increase in sample acidity.

In order to determine more accurately the effect of moist air, O-59-26 and O-60-27 were subjected to further testing using a nominal relative humidity of 50 percent. This moisture condition was attained by simply metering equal volumes of dry and "water-saturated air" through the sample. The two air streams were directed to a common line attached to the test cell air tube. The data for the three air conditions are given in Table 22. In general, the 50 percent RH results were quite comparable to the results obtained with 100 percent RH. Although both lubricants indicated improved performance when using moist air, the greatest effect occurred in the region of 0 to 50 percent RH.

This phenomenon is of particular interest in regard to the test procedure used for the wet air tests. Because of the negligible differences in test results shown between 50 and 100 percent RH, very closely controlled saturation conditions do not appear necessary for the water-saturated tests.

Additional studies on the effect of moist air were conducted on several lubricants over the temperature range of 425 to 500°F. The results of this test series are given in Table 23 for seven lubricants. For comparison, data are also presented for tests with dry air, many of which were listed in Part I[1] of this report. The comparison is somewhat complicated by the fact that some earlier tests were performed in the oil bath apparatus. In those instances, sample temperature was some 2 or 3°F below the stated test temperature. The result of this temperature difference does not, however, obscure the overall effect exhibited by wet air.

The data of Table 23 indicate that the effect produced by wet air was dependent not only upon lubricant type but also, in the case of individual oils, upon sample temperature. Only two fluids, MLO-62-1012 and MLO-62-1005, appear to have been generally unaffected by humidity throughout the temperature range investigated. The dependence upon sample temperature was illustrated by MLO-62-1008 and MLO-62-1011. At 425°F,

TABLE 21. EFFECT OF AIR HUMIDITY ON 425°F 18-HR OXIDATION-CORROSION TEST RESULTS

Oil Code	Initial Viscosity at 100°F, cs	% Viscosity Increase at 100°F		Initial Neut. No., mg KOH/g	Final Neut. No., mg KOH/g	
		Dry Air	Wet Air		Dry Air	Wet Air
O-58-24	34.44	527	268	0.12	17.71	19.11
O-59-15	18.67	5	3	0.06	1.08	1.14
O-59-26	18.61	218	10	0.10	10.73	0.61
O-60-12	16.17	8	8	0.07	0.38	0.53
O-60-19	20.89	4	10	0.15	2.12	3.70
O-60-23	16.00	67	8	0.06	6.20	0.41
O-60-27	15.02	131	26	0.11	9.31	0.71
O-61-19[a]	15.69	254	88	0.10	11.14	7.07

Data presented represent single determinations.

(a) Same nominal formulation as O-60-27.

TABLE 22. EFFECT OF AIR HUMIDITY ON 425°F 18-HR OXIDATION-CORROSION TEST RESULTS FOR TWO MIL-L-9236 TYPE LUBRICANTS

	Nominal RH of Air, %		
	0	50	100
		O-59-26	
% Viscosity increase at 100°F	218	23	10
Final neut. no., mg KOH/g	10.7	2.3	0.6
Oil loss, g	52	29	27
		O-60-27	
% Viscosity increase at 100°F	131	28	26
Final neut. no., mg KOH/g	9.3	0.8	0.7
Oil loss, g	92	82	81

TABLE 23. EFFECT OF AIR HUMIDITY ON 18-HOUR OXIDATION-CORROSION TEST RESULTS AT VARIOUS TEMPERATURES

Sample Temperature, °F	425		450		475		500	
Nominal RH of Air, %	0	100(a)	0	100(a)	0	100(a)	0	100(a)
O-60-23								
% Vis Increase at 100°F	67	8	1220(b)	784				
Neut. no., mg KOH/g	6.2	0.4	10.6	10.9				
O-60-27								
% Vis Increase at 100°F	131	26	980(b)	1103				
Neut. no., mg KOH/g	9.3	0.7	13.3	11.1				
MLO-62-1008								
% Vis Increase at 100°F	32(b)	31	158(b)	72	890(b)	778		
Neut. no., mg KOH/g	3.3	1.0	11.2	4.8	11.9	11.7		
MLO-62-1011								
% Vis Increase at 100°F	3(b)	4	9(b)	118	1100(b)	5700		
Neut. no., mg KOH/g	0.1	0.2	0.2	3.4	10.7	5.8		
MLO-62-1012								
% Vis Increase at 100°F	22(b)	22	45(b)	48	210(b)	241		
Neut. no., mg KOH/g	1.0	0.8	2.1	2.1	5.9	5.7		
ATL-304								
% Vis Increase at 100°F	39	34	82	70	394	269		
Neut. no., mg KOH/g	1.8	0.2	3.9	3.6	8.3	7.6		
MLO-62-1005								
% Vis Increase at 100°F	-	-	-	-	23(b)	21	34(b)	28
Neut. no., mg KOH/g	-	-	-	-	0.1	0.2	0.3	0.2

(a) Data for 100 percent RH air are averages of duplicate tests.

(b) Test run in oil bath apparatus.

neither lubricant was significantly affected by wet air; however, at 450 and 475°F, viscosity results showed a measurably altered performance between dry and wet air tests. Further, note that the effect of humidity on sample viscosity at the higher temperatures was in opposite directions for these two oils. This essentially unpredictable effect of humidity was also reflected by the other oils, and is apparently dependent upon the oil formulation.

Aside from the viscosity and acidity data given in Table 23, no other significant change in oil performance was observed in the wet air tests. In particular, there was no noticeable difference in the lubricants' metal corrosion properties between the dry and wet air tests.

C. High-Temperature Oxidation-Corrosion Test

1. Test Procedure and Apparatus

At the present time, only general concepts, such as the approximate temperature range, exist regarding the conditions of operation of the supersonic transport engine. Therefore, it was not feasible to attempt the development of a specific test characterizing a lubricant's performance in the supersonic transport engine. Consequently, the objective of this investigation has been to evaluate the oxidation-corrosion characteristics of candidate lubricants over a wide range of test conditions.

Under Contract AF 33(657)-9248, a high-temperature oxidation-corrosion test apparatus using a forged aluminum heating block with provision for eight sample tubes was designed, constructed, and placed in operation[1]. The associated test glassware is of the same design as that used in the 18-hr test conducted in the aluminum block, and is described in Part I[1] of this report. In the later stages of this work, use of the normal test cell head was abandoned in favor of the test cell head specified for the CRC test procedure discussed in a subsequent section. At the time of this change, several lubricants were examined with the new head in repeat runs of previous tests obtained with the original glassware. No noticeable effect was observed in any of the measured test results using air flow rates over a range of 10 to 130 liters/hr. Therefore, no distinction between test data obtained with the two head types is noted in the following discussion on results.

2. Test Results and Discussion

As a consequence of the use of intermediate sampling procedures, a considerable volume of data has been generated in this work. Therefore, for the sake of brevity, data presentations are confined in most cases to summary tabulations or illustrations.

a. <u>Oxidation-Corrosion Characteristics of 5P4E Polyphenyl Ether</u>

Considerable background data have been previously reported[1] for a 5P4E polyphenyl ether lubricant. The present report describes additional studies on 5P4E polyphenyl ether using varied test conditions of temperature, metal specimens, air flow, nitrogen-air mixtures, and reflux of condensable vapors.

Two batches of 5P4E polyphenyl ether have been used in these investigations. The first batch, LRO-13, was on hand at the initiation of this program and was used for the preliminary studies of test variables and repeatability[1]. The supply of LRO-13 was depleted during the previous contract, and a supply of the second batch, F-1041, was procured for use as a reference fluid for the entire program. Although tests with F-1041 indicated the same performance for both batches, the evaluations and data comparisons of fluid performance have been confined to the use of results from one or the other batch, i.e., data from the two fluids have in no case been intermixed. In the present report, all results were obtained with F-1041. Complete inspection data on this material have been previously reported[1].

Using a five-metal specimen set (Al, Ti, Ag, mild steel, stainless steel), the major test variables studied with 5P4E were sample temperature, air flow rate, and condensate return. Tables 24 through 26 summarize the results of these investigations at sample temperatures of 550, 600, and 650°F, respectively.

In tests conducted with condensate return, the reflux glassware assembly used was a water-cooled Allihn condenser attached immediately above the sample tube by means of a ground-glass reducing adapter.

As evidenced by results shown in Table 24, lubricant degradation was very moderate at 550°F with 5P4E. Viscosity data reflect a minimum viscosity increase at an air flow of about 35 liters/hr; however, viscosity differences among the various air flow determinations were very slight. The effect of condensate return on sample viscosity was likewise negligible at this temperature.

Extensive data at 600°F without condensate return have been previously reported[1] for LRO-13. Similar performance is indicated for F-1041, with summary data shown in Table 25. Substantial oxidation of the fluid occurred at 600°F as reflected by sample viscosity increase. As for LRO-13, an anomaly was apparent in that a maximum in viscosity increase

TABLE 24. SUMMARY OF OXIDATION-CORROSION TEST RESULTS ON F-1041 AT 550°F

Air Rate, liters/hr	48-hr Sample: % Vis Increase at 100°F	48-hr Sample: Neut. No., mg KOH/g	Overhead Product: Vis, cs/100°F	Overhead Product: Neut. No., mg KOH/g	Overhead Product: Wt, g
		Without Condensate Return			
130	15.8	0.0	342.4	0.02	107
75	11.9	0.0	341.3	0.06	64
50	11.8	0.06	312.9	0.08	44
35	11.3	0.02	282.5	0.08	30
20	13.3	0.0	(a)	0.15	16
16	13.9	0.03	(a)	0.28	14
5	15.5	0.06	(a)	(a)	4
		With Condensate Return		Oil Loss, g	
75	11.6	0.0		76	
50	11.4	0.01		51	
35	12.3	0.02		32	
27	13.7	0.04		14	
20	14.3	0.04		13	
16	15.8	0.06		8	
5	11.2	0.08		6	

Metal specimens: Al, Ti, Ag, steel, stainless steel.
Sample volume: 200 ml.

(a) Insufficient sample available.

TABLE 25. SUMMARY OF OXIDATION-CORROSION TEST RESULTS ON F-1041 AT 600°F

	48-hr Sample		Overhead Product		
Air Rate, liters/hr	% Vis Increase at 100°F	Neut. No., mg KOH/g	Vis, cs/100°F	Neut. No., mg KOH/g	Wt, g
		Without Condensate Return			
75	76	0.11	310.8	0.0	156
	72	0.09	303.3	0.0	150
50	67	0.02	274.6	0.29	99
	81	0.12	256.9	0.12	101
35	90	0.11	218.8	0.29	69
27	147	0.22	154.4	0.47	51
	132	0.18	145.3	0.47	47
20	165	0.17	128.7	0.65	42
	149	0.30	118.9	0.12	36
16	190	0.19	83.9	2.06	30
	169	0.34	102.7	0.82	34
5	170	0.35	39.96	1.99	13
	190	0.26	(a)	1.95	12
3	125	0.24	(a)	1.78	11
		With Condensate Return			
				Oil Loss, g	
75	77	0.10		86	
	86	0.03		78	
50	190	0.24		56	
	254	0.29		38	
35	440	0.49		38	
	1450	1.14		21	
27	1850	1.03		23	
	3050	1.28		13	
20	1500	1.12		16	
	1140	0.94		18	
	1090	1.14		11	
16	1140	0.90		12	
	1450	1.05		9	
5	346	0.85		9	
	285	0.90		6	

Metal specimens: Al, Ti, Ag, steel, stainless steel.
Sample volume: 250 ml

(a) Insufficient sample available.

TABLE 26. SUMMARY OF OXIDATION-CORROSION TEST RESULTS ON F-1041 AT 650°F

Air Rate, liters/hr	24-hr Sample: % Vis Increase at 210°F	24-hr Sample: Neut. No., mg KOH/g	Overhead Product[a]: Vis, cs/100°F	Overhead Product[a]: Neut. No., mg KOH/g	Overhead Product[a]: Wt, g
		Without Condensate Return			
75	169	0.29	234.4	0.27	209
50	415	0.40	113.4	1.21	139
35	353	0.34	78.7[b]	2.04	95
20	233	0.31	47.5	2.49	19
12	183	0.34	37.5	2.40	13
5	83.5	0.29	23.2	3.48	6
		With Condensate Return			
				Oil Loss at 24 hr, g	
130	5880	(c)		92	
75	3530	(c)		56	
50	1185	(c)		15	
35	1070	(c)		12	
20	418	(c)		5	
16	271	0.25		9	
5	69.8	0.09		9	

Metal specimens: Al, Ti, Ag, steel, stainless steel.
Sample volume: 250 ml.

(a) Overhead product properties for determinations at 75, 50, and 35 liters/hr are 40-hr values, all others are 48-hr values.

(b) Dark red crystal formation in sidearm of test tube head--distinct odor of phenol.

(c) Sample insoluble in titration solvent.

was encountered (at approximately 12 liters/hr) as air flow was varied from 3 to 75 liters/hr. 48-hr test data could not be obtained at air rates greater than 75 liters/hr because of high oil losses experienced. In all cases, sample neutralization number remained very low.

Similar tests on F-1041 at 600°F, but with the use of a condensate return glassware system (Table 25), revealed the same general trend for the effect of air flow. However, the level of 5P4E deterioration was much higher for all air flows except the determinations at 75 liters/hr. At this flow the tests indicated no significant difference in viscosity data with or without condensate return. In evaluating the effect of reflux of condensable products, it should be noted, however, that condenser efficiency was significantly reduced at the higher air flow rates. At 75 liters/hr, for example, net oil loss in a reflux test was approximately 50 percent of that experienced in a nonreflux test. Thus, for most tests employing condensate return, only a partial return of effluent products was obtained, with the degree of return dependent on the rate of air flow.

In order to evaluate the oxidation properties of 5P4E under an extreme temperature condition, a brief test series was conducted at 650°F. These results are given in Table 26 for both reflux and nonreflux tests. Because of severe thickening of the material, the maximum test duration for sample evaluation was 24 hr. In addition, sample viscosity measurements given in Table 26 are at 210°F, since the material in most cases was nearly gelled at the usual viscosity reference temperature of 100°F. As an approximation, viscosity increase at 100°F would be about two to three times that at 210°F.

The 650°F test series without condensate return, as for the 600°F series, exhibited a maximum in viscosity increase within the range of air flows studied. At the 650°F temperature, however, this maximum occurred at a much higher air flow, approximately 50 liters/hr. The run at 35 liters/hr demonstrated a unique phenomenon by the formation of dark red, needle-like crystals in the overhead sidearm tube. The crystals had a very strong odor of phenol, but no attempt was made to identify the material by analysis.

Test results at 650°F with condensate return likewise showed extensive deterioration of 5P4E. Except for the 5 liters/hr run, the deterioration was much more extreme than corresponding tests using the nonreflux configuration. Note that the series at 650°F with condensate return gave consistent lubricant deterioration with increasing air flow. All other test series indicated a maximum viscosity increase within the air flow range investigated. This observation is illustrated graphically by Figure 1 which

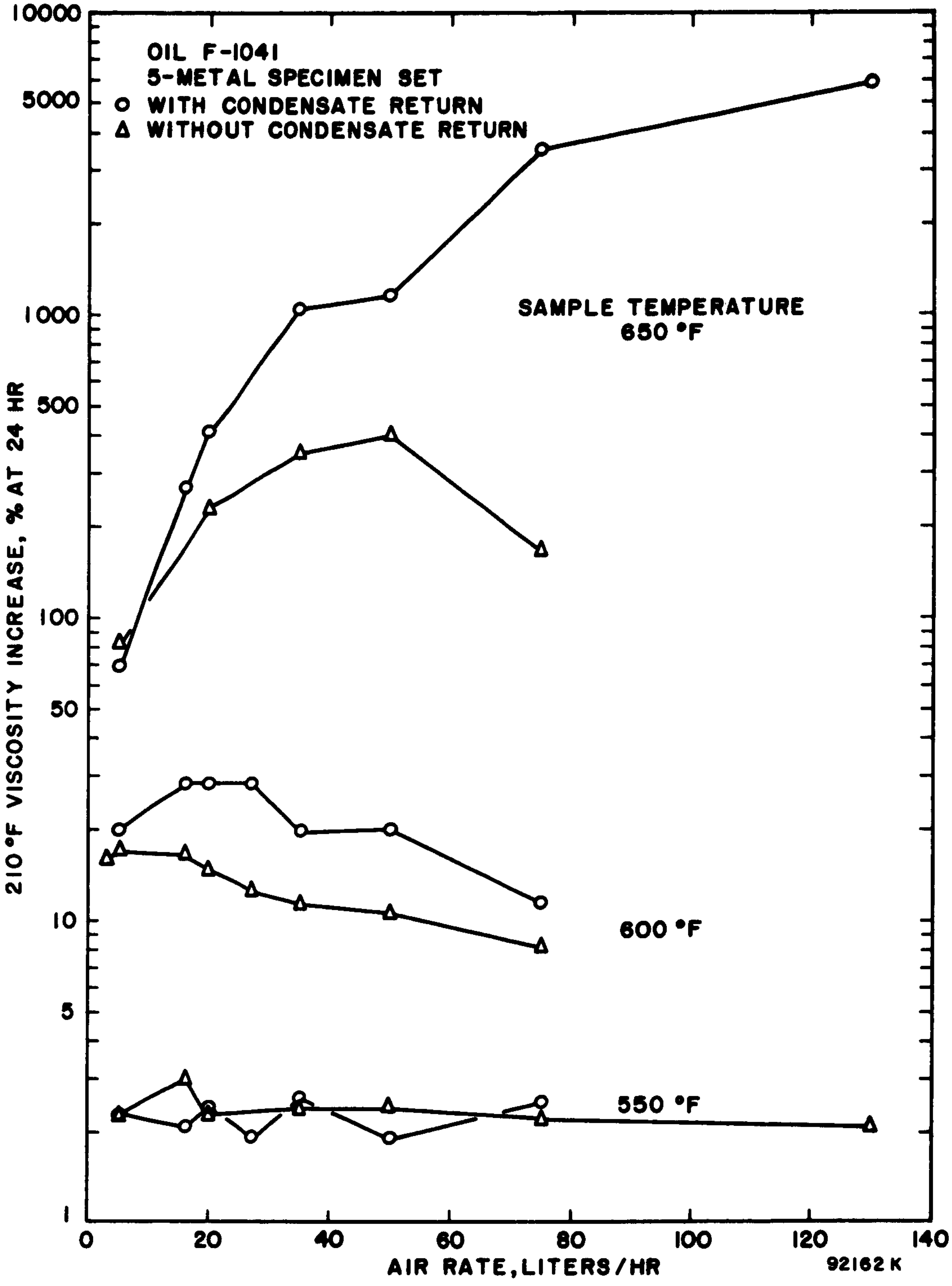

FIGURE 1. EFFECT OF SEVERAL TEST VARIABLES ON 5P4E LUBRICANT DETERIORATION

permits an assessment of 5P4E performance as affected by the test variables of temperature, air flow, and condensate return.

A possible explanation for the unexpected air flow effect on 5P4E degradation was tentatively given previously[1] in terms of a vapor-phase oxidation phenomenon. Then, as now, a positive description of the mechanism involved is not available. However, recent results obtained with condensate return suggest an alternate explanation concerning a possible catalytic effect on sample oxidation by volatile products of the oxidation reaction. The test series at 600°F, for example, exhibited a significant increase for 5P4E degradation when reflux of condensable oil and vapors was accomplished. This effect was noted for all air flow rates except the highest, 75 liters/hr. This would suggest that a relatively volatile component served to promote oxidation, catalytically or otherwise, at the lower air rates, but indicated no effect at 75 liters/hr since the product was probably totally removed from the sample tube by the high air flow.

In applying this theory to an interpretation of the 5P4E data for 600°F, it might be conjectured that the curve maximum was the result of sample oxidation and internal refluxing of the volatile component. As air flow was increased, a successively larger portion of the component was probably removed, and its net effect on the reaction was successively lessened. It should be emphasized that this explanation can be offered only as conjecture with present knowledge, and is considered only as a possible alternative to the theory of vapor-phase oxidation.

Additional air studies with 5P4E are described by the data presented in Figure 2. The upper curve illustrates the 600°F test results without condensate return as given in Table 25. These data are compared with a test series employing various nitrogen-air mixtures. For the latter, the total gas flow was maintained at 75 liters/hr but the volume ratio of nitrogen to air was varied. The two gases were metered individually but were premixed and admitted to the sample through one flow tube.

As illustrated by the figure, a substantial effect was obtained. In the nitrogen-air tests, a gradual and consistent increase in lubricant deterioration was demonstrated as the air percentage was raised. The determination with 75 liters/hr nitrogen flow and no air gave a viscosity increase of 8 percent, due possibly to some thermal instability or the presence of dissolved air in the fluid prior to test. The extreme difference between the two curves was presumably due to the unknown phenomenon possibly connected with vapor-phase oxidation or the catalytic effect of oxidation products. In the nitrogen-air tests, it is felt that the effect of this phenomenon was

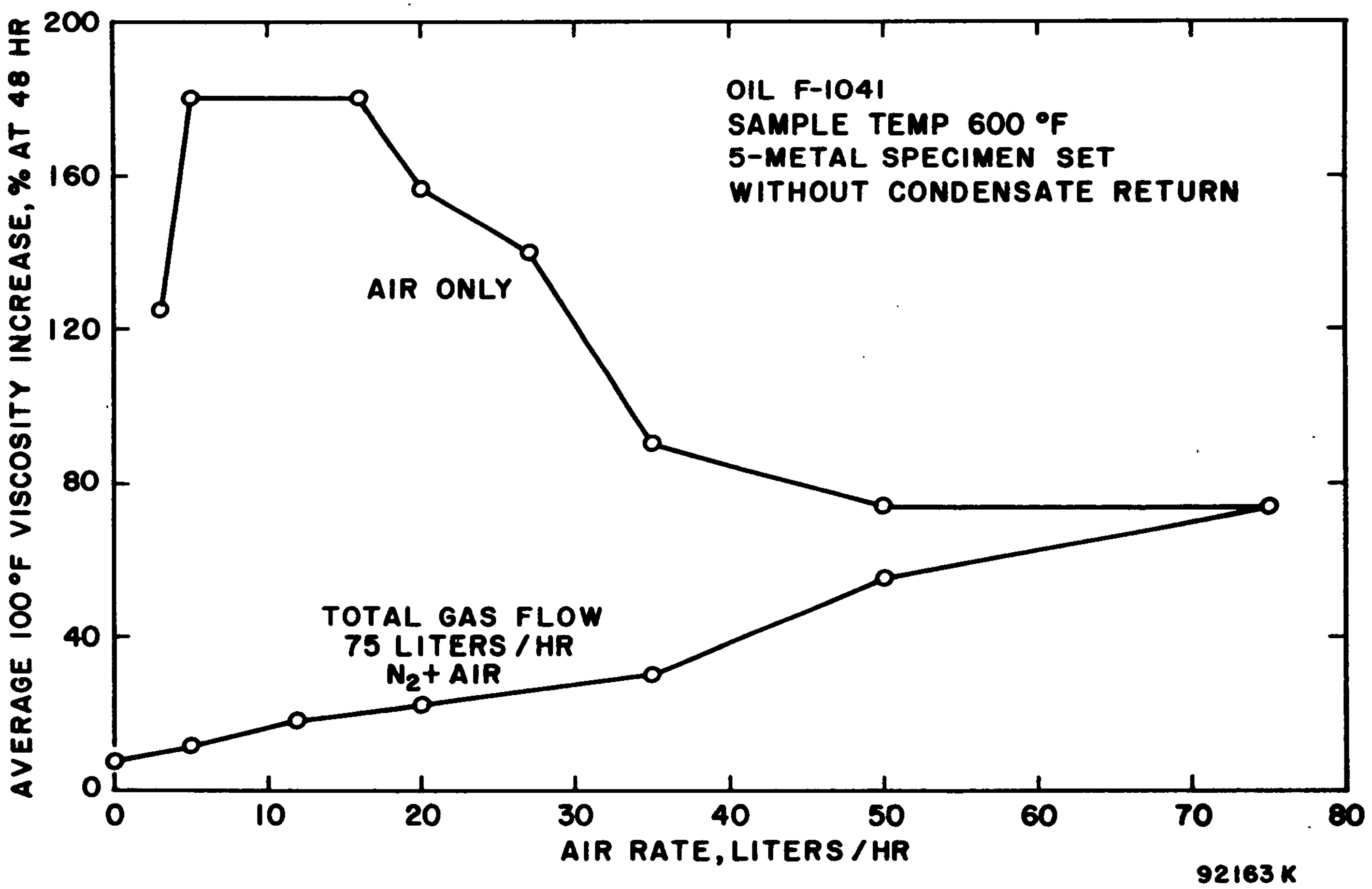

FIGURE 2. EFFECT OF NITROGEN-AIR MIXTURES ON 5P4E LUBRICANT DETERIORATION AT 600° F

minimized or at least held constant. While these results seem to verify the presence of a significant factor in the oxidation mechanism of 5P4E, the data do not conclusively identify the nature or the cause of the phenomenon.

Further studies were conducted using nitrogen-air mixtures in an attempt to gain information which might provide additional insight concerning the unusual reaction of 5P4E to varying air flow rate. A descriptive plot of viscosity data obtained in this test series is given in Figure 3. The results are presented as a function of total gas flow rate and volume percent oxygen content, with the upper curve representing test data obtained with air only (21 percent oxygen).

Unfortunately, the test series with nitrogen-air mixtures did not give any tangible clarification concerning the anomalous effect produced by varying test air rate. The study did reveal some interesting factors relating 5P4E performance to gas flow rate and oxygen content. Examination of Figure 3 indicates that 5P4E deterioration showed little or no dependence upon total gas flow rate, provided oxygen content was maintained below a certain volume percentage. Although relatively few data were obtained in the low regions, it appears that with an oxygen content of about 10 percent or less there was no effect exhibited by gas flow rate over the range investigated. As the oxygen percentage was increased above this value, the influence of gas flow rate gradually became more pronounced, and the curves for a fixed oxygen content began to assume the shape of that shown for air alone. It might be conjectured that a practical application of this phenomenon could be profitably explored in a lubricant system utilizing 5P4E. Figure 3 indicates that a significant improvement in lubricant performance could be obtained by a reduction of the oxygen content of the lubricant system atmosphere.

b. <u>Effect of Condensate Return on 5P4E Polyphenyl Ether</u>

As a consequence of the significant differences in 5P4E test results produced by the use of a condensate reflux system, a brief study was made to evaluate the effect of reflux using different condenser types. Table 27 lists data obtained at 600°F for F-1041 when tested with varying degrees of condensate return at the selected air rates of 20 and 75 liters/hr. The Allihn condenser is the type normally used in reflux testing. The results of Table 27 reveal a general division for the degree of condensate return and 5P4E lubricant viscosity data at both air flows. A condenser efficiency (calculated on the basis of oil loss difference between nonreflux and reflux tests) of about 50 percent or less had no significant effect on results. At higher condenser efficiencies, however, a deleterious effect on oxidation stability was observed, particularly for the lower air flow condition. This relationship is in line with the previous observation concerning a possible explanation for

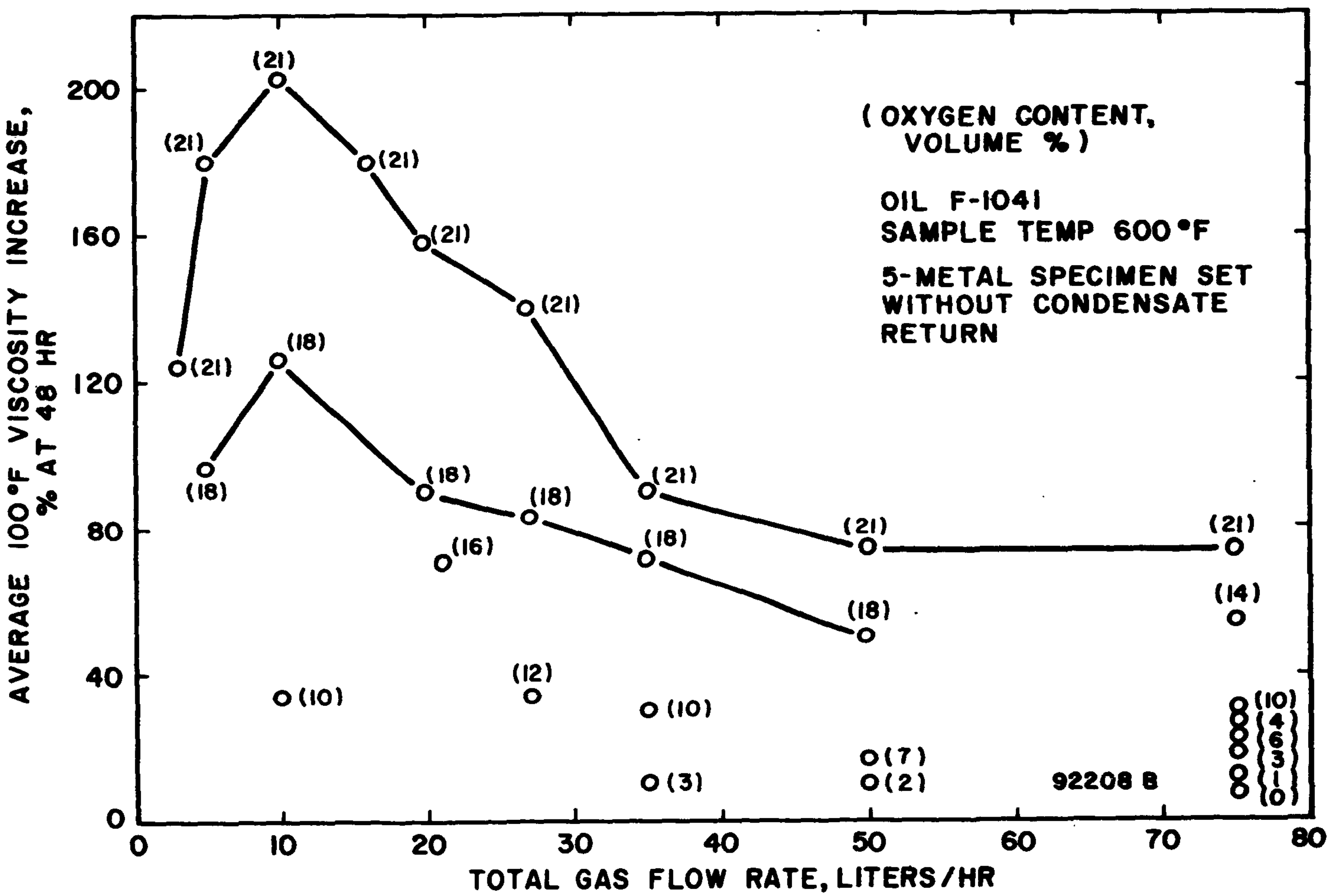

FIGURE 3. EFFECT OF NITROGEN-AIR MIXTURES ON 5P4E LUBRICANT DETERIORATION AT 600°F

TABLE 27. EFFECT OF CONDENSATE RETURN ON 600°F OXIDATION-CORROSION TEST RESULTS FOR F-1041

Condenser Type	Condenser Efficiency, %	48-hr Sample: % Vis Increase at 100°F	48-hr Sample: Neut. No., mg KOH/g	Net Oil Loss, g
		20 liters/hr Air Rate		
Nonreflux	-	157	0.24	44
600-mm Air	36	177	0.26	28
400-mm Allihn[a]	70	1240	1.05	13
300-mm Graham[a]	100	936	0.83	0
		75 liters/hr Air Rate		
Nonreflux	-	74	0.10	155
600-mm Air	23	62	0.03	120
400-mm Allihn[a]	47	82	0.07	82
300-mm Graham[a]	87	181	0.03	20

Five-metal specimen set.

(a) Water-cooled condenser.

the anomalous effect exhibited by air flow rate. At the lower condenser efficiencies, a major portion of the vapor losses to atmosphere undoubtedly consisted of rather volatile oxidation products. As the process of condensation was made more efficient, a greater percentage of these products was returned to the sample tube with the attendant acceleration of 5P4E deterioration.

c. Effect of Metals on 5P4E Polyphenyl Ether

Earlier studies[1] with LRO-13 in an examination of the influence of certain metal specimen groups on the oxidation of 5P4E at 600° F showed no difference between tests without metals and those with a five-metal specimen set (Al, Ti, Ag, steel, stainless steel). Use of a seven-metal (Cu and Mg added to five-metal set) specimen group, however, gave a distinct suppression of lubricant oxidation. During the present report period, this work was extended to include studies at test temperatures of 550 and 650° F with the five- and seven-metal groups.

At 550° F the presence of copper and magnesium produced a slight improvement in 5P4E performance as reflected by viscosity increase at the end of the 48-hr test period. At all air rates investigated, however, the effect at 550° F was negligible as illustrated by the results given in Table 28.

When tested at 650° F, the oxidation resistance of the fluid was considerably enhanced by the use of the seven-metal group, both with and without condensate return. As shown in Table 28, viscosity increase at 650° F in seven-metal tests was reduced by several magnitudes in comparison with the five-metal test series. The improved performance of F-1041 using seven metals was presumably due to presence of the copper specimen which has been reported to serve as an effective antioxidant for 5P4E[2].

d. 5P4E Results for Metal Specimen Corrosion

Instances of significant metal specimen attack by 5P4E occurred at 600[1] and 650° F, and were confined to three metal types: silver, copper, and magnesium. Table 29 provides a listing of weight changes obtained at 650° F for these metals. As in the 600° F tests, silver attack in the 650° F tests was generally random with no apparent relationship between weight loss and oil performance. In addition, one case of substantial weight gain was shown for silver in the determination at 5 liters/hr air flow without condensate return. Metal weight change for silver in tests with reflux gave some indication that corrosion of this metal could be expected in those tests which employed the seven-metal specimen group. However, sufficient data are not available to allow a generalized observation in this respect.

TABLE 28. EFFECT OF METALS ON OXIDATION-CORROSION TEST VISCOSITY RESULTS FOR F-1041

	Air Rate, liters/hr						
	5	16	20	35	50	75	130
550°F Sample Temperature			Without Condensate Return				
48-hr viscosity increase/100°F, %							
5-metal set	15.5	13.9	13.3	11.3	11.8	11.9	15.8
7-metal set	14.2	11.6	11.6	11.2	10.1	11.7	14.6
650°F Sample Temperature			Without Condensate Return				
24-hr viscosity increase/210°F, %							
5-metal set			233		415		
7-metal set			96.3		67.1		
			With Condensate Return				
5-metal set			418		1185		
7-metal set			238		180		

5-metal set: Al, Ti, Ag steel, stainless steel.
7-metal set: 5-metal set plus Cu and Mg.

TABLE 29. CORRELATION OF OXIDATION-CORROSION TEST VISCOSITY DATA WITH BEARING TEST RESULTS FOR F-1041

Air Rate, liters/hr		Percent Viscosity Increase at 210°F			
		600°F Oil Temperature(b)		650°F Oil Temperature(c)	
O-C Test	Bearing Test(a)	16-hr O-C Test Sample	48-hr Bearing Test Sample	16-hr O-C Test Sample	48-hr Bearing Test Sample
		Without Condensate Return			
20	20	12	10	80	72
75	76	9	10	52	58
		With Condensate Return(d)			
20	20	11	11	135	66, 103 (46 hr)
75	76	7	8	183	97

(a) Total air flow (air to oil sump plus air to test head) proportional to a 250-ml oil sample volume.

(b) Bearing test conditions: 600°F oil sump, 650°F bearing.

(c) Bearing test conditions: 650°F oil sump, 700°F bearing.

(d) The "condensate return" case for the bearing test refers to tests whereby the test oil recovered from the vent trap is returned to the test oil sump (explained fully in the next chapter of this report).

Although only four determinations were made at 650°F with the specimen group containing copper and magnesium, in every case a significant weight loss was shown for copper. This was probably connected with the role of copper as an effective 5P4E antioxidant. Magnesium indicated a general resistance to 5P4E corrosion at 650°F. One test at 20 liters/hr air rate with reflux gave a measurable weight gain for magnesium due to the formation of deposits not removable by the usual cleaning procedure.

e. Correlation of Oxidation-Corrosion Test Results with Bearing Test Data

To establish some measure of the validity and applicability of the high-temperature oxidation-corrosion test, some effort was directed toward an evaluation of existing correlation between data from the oxidation-corrosion test and the 100-mm bearing test using 5P4E (discussed in the next chapter). In this evaluation, several considerations must be taken into account so that results are correlated under conditions comparable for both tests. At the present time, it is felt that reasonable confidence exists in the establishment of corresponding test conditions with respect to test duration and temperature. Considerably less reliability is placed in the correspondence between tests for air flow rate and the condensate return process. It should be emphasized that no concerted effort was made to effect correlation between the oxidation-corrosion test and the bearing deposit test using the 5P4E polyphenyl ether. The present evaluation of correlation was simply based on existing data obtained in the course of test-variable studies.

An illustration of test correlation for lubricant viscosity data is given in Table 29 for the conditions used for comparison. As shown, excellent correlation was evident between oxidation-corrosion test results and bearing test data in three cases: 600°F sample temperature with and without condensate return, and 650°F without return. However, the comparison at 650°F with condensate return indicated poor correspondence of data. Oxidation-corrosion test results showed a more severe level of deterioration than the comparable bearing tests at both air flow rates. This discrepancy is believed to be due to the significant differences present in the efficiency and means of condensate return between the two tests. An additional factor may have been the effect of water-saturated air on oil deterioration. The normal bearing test procedure requires that air admitted to the apparatus be nominally water saturated by the use of a gas diffuser and water flask, whereas the air supply for the oxidation-corrosion test was pretreated and filtered to attain essentially absolute dryness.

f. Oxidation-Corrosion Test Results on MLO-62-1005

Previous studies[1] on MLO-62-1005 showed that it was the only oil, aside from 5P4E polyphenyl ether, that gave less than 100 percent viscosity increase in an 18-hr 500°F oxidation-corrosion test in the oil bath test apparatus. In an additional 500°F test in the aluminum block apparatus, its viscosity increase was less than 100 percent after 24 hr; however, severe gelation occurred at the end of 40 hr.

During the present period, MLO-62-1005 was evaluated at 475°F in the high-temperature apparatus in an attempt to extend the oil's performance duration to 48 hr, and to examine the effect of air flow rate on this lubricant.

The 48-hr test results on this oil are given in Table 30. The oxidation stability of the fluid with respect to sample viscosity increase and neutralization number was good at 130 liters/hr air flow. The determination with MLO-62-1005 at 5 liters/hr gave an excessive increase in sample viscosity. Higher air rates showed less severe deterioration, with a minimum viscosity increase occurring at approximately 35 liters/hr. In addition, excessive amounts of sludge and carbon deposit were noted at the lower air flows as described in Table 31.

MLO-62-1005 samples tested at 35 liters/hr and below contained a finely divided particle suspension which gave some interference in viscosity measurements. Thus, viscosities are shown in Table 30 for those samples both with the suspension present and after removal of the suspension by centrifuging.

Significant metal specimen attack was evident in this test for mild steel and silver, as shown below:

Air Rate,	Weight Change, mg/cm^2						
liters/hr:	5	16	20	35	50	75	130
Steel	-16.45	-1.75	-1.15	-0.54	-0.45	-0.31	0.0
Silver	+0.04	-0.02	-0.05	-0.09	+0.04	-0.32	-0.27

Earlier work indicated the tendency of this fluid to corrode mild steel[1], but the 16 mg/cm^2 loss recorded with 5 liters/hr air rate has been the most severe instance of steel attack.

TABLE 30. SUMMARY OF OXIDATION-CORROSION TEST RESULTS FOR MLO-62-1005 AT 475°F

	48-hr Sample		Overhead Product		
Air Rate, liters/hr	% Vis Increase at 100°F	Neut. No., mg KOH/g	Vis, cs/100°F	Neut. No., mg KOH/g	Wt, g
5	965 (950)[a]	3.66	(b)	(b)	15
16	49 (42)	0.88	10.73	168	9
20	44 (41)	0.85	12.97	136	15
35	37 (36)	0.30	18.54	116	15
50	42	0.18	20.40	100	18
75	54	0.34	24.04	88.0	20
130	63	0.34	30.11	79.1	20

Metal specimens: Al, Ti, Ag, steel, stainless steel. Without condensate return.

Sample volume: 200 ml.

(a) Values in parentheses indicate viscosity increase based on centrifuged sample.

(b) Insufficient sample. Two-phase liquid collected in overhead receiver: upper fluid light, clear yellow; lower fluid clear, colorless.

TABLE 31. GLASSWARE AND OIL SLUDGE APPEARANCE FOR 475°F OXIDATION-CORROSION TEST ON MLO-62-1005

Air Rate, liters/hr	Glassware Appearance	Sludge 200-Mesh Filter Screen	Sludge 1-hr Centrifuge
5	Heavy sludge below oil level--heavy carbon deposit on air tube and metals	Trace	Indistinguishable[a]
16	(Same as 5)	Approx 4g/50 ml	Indistinguishable[a]
20	(Same as 5)	4.8 g	Indistinguishable[a]
35	Slight carbon deposit 2 in. above oil level, approx 2 in.^{2} area	None	Indistinguishable[a]
50	(Same as 35)	None	None
75	(Same as 35)	None	None
130	(Same as 35)	None	None

Metal specimens: Al, Ti, Ag, steel, stainless steel. Without condensate return.
Sample volume: 200 ml

(a) Finely divided particles suspended in oil sample.

g. Oxidation-Corrosion Test Results on ATL-307

This high-temperature lubricant candidate was evaluated in 48-hr oxidation-corrosion tests over a temperature range of 500 to 600°F. Lubricant performance data are summarized in Table 32. As discussed in succeeding chapters, ATL-307 was also investigated in the 100-mm bearing test and the gear load-carrying capacity test. An air flow rate of 20 liters/hr was selected for the oxidation-corrosion test work because previous studies indicated a reasonable correspondence with bearing test lubricant data under these conditions, and it was desired that the oxidation-corrosion investigations supplement the bearing test evaluation on this oil.

As illustrated in Table 32, the fluid showed remarkably good oxidation stability throughout the temperature range examined. A performance comparison between ATL-307 and earlier data on 5P4E polyphenyl ether indicated the former lubricant was considerably more superior on the basis of viscosity increase under comparable test conditions. For example, the 600°F test with ATL-307 gave a 100°F viscosity increase of 15.1 percent. The corresponding result obtained with 5P4E was 157 percent (average).

Although ATL-307 demonstrated excellent oxidation characteristics in the 48-hr test, the metal corrosion properties of the fluid were quite poor, particularly at 550 and 600°F. Results presented in Table 33 show a significant weight gain for aluminum, steel, and stainless steel at 550°F, while titanium underwent a measurable weight loss due to corrosion of the metal. In general, metal attack followed the same trend at 600°F except for the increased severity. In addition, a 0.31 mg/cm^2 loss was obtained with silver at the higher temperature. Those metal specimens which experienced a weight gain had a deposit or coating, as described in Table 33, which was not removable by the normal post-test cleaning procedure. The most unusual aspect of the corrosive tendency of ATL-307 was its attack on titanium. In all previous experience with other lubricant types, this metal has been unaffected in the high-temperature test and also in the 18-hr oxidation-corrosion test.

Glassware deposits in the ATL-307 tests were not, with respect to appearance, in the classification of the usual carbonaceous types. No deposits were obtained at 500 or 525°F, and there was essentially no change in lubricant sample appearance. The 550 and 600°F tests were similar in deposit appearance; however, the following descriptions were more emphasized at the higher test temperature. A milky, white coating was obtained in the glass sample tube, chiefly below the lubricant level. In addition, some of this material was apparently in suspension within the oil sample. The sample tube deposit was soft and easily removed in some areas, but generally

TABLE 32. SUMMARY OF HIGH-TEMPERATURE OXIDATION-CORROSION TEST RESULTS ON ATL-307

Sample Temperature, °F	48-hr Vis Increase, %[a]		Overhead Product		Oil Loss, g
	at 100°F	at 210°F	Vis, cs at 100°F	Wt, g	
500	8.7	5.4	(b)	13	29
525	8.8	5.9	64.60	24	36
550	13.4	9.2	90.95	37	53
600	15.1	10.8	101.9	62	81

Air rate: 20 liters/hr.
Metal specimens: Al, Ti, Ag, steel, stainless steel.
Without condensate return.

(a) Initial viscosity, cs: 286.9 at 100°F, 25.69 at 210°F.

(b) Insufficient sample.

TABLE 33. SUMMARY OF METAL SPECIMEN WEIGHT CHANGES AND APPEARANCES FOR HIGH-TEMPERATURE OXIDATION-CORROSION TESTS ON ATL-307

Metal Type	Sample Temperatures, °F			
	500	525	550	600
Aluminum	-0.04 mg/cm^2 No change.	+0.16 mg/cm^2 Light grey coloration.	+0.22 mg/cm^2 Dark grey spots covered approx. 20%, otherwise unchanged.	+0.47 mg/cm^2 Dark grey coloration.
Titanium	-0.05 mg/cm^2 Dark grey coloration.	-0.19 mg/cm^2 Brown and purple coloration.	-0.56 mg/cm^2 Large corrosion area, blue coloration, covered by a white coating.	-2.06 mg/cm^2 Deep blue coloration.
Silver	-0.07 mg/cm^2 No change.	-0.16 mg/cm^2 White coloration.	-0.10 mg/cm^2 White coloration, covered approx. 30% by dark brown spots.	-0.31 mg/cm^2 White coloration.
Steel	-0.02 mg/cm^2 Blue coloration.	+0.14 mg/cm^2 Brown and red coloration.	+0.20 mg/cm^2 Isolated pitting, rusty appearance.	+1.35 mg/cm^2 Rusty appearance.
Stainless Steel	-0.07 mg/cm^2 Brown coloration.	-0.10 mg/cm^2 Slight blue tint.	+0.23 mg/cm^2 Yellow and brown, with 20% being blue white colored.	+0.14 mg/cm^2 No discoloration.

the coating was of a hard, ingrained consistency. A close examination of the tube also revealed a severe, uniform pitting of the glass inthe deposit areas.

h. Effect of Air Flow Rate on Oxidation-Corrosion Test Results for Several Lubricants

Much consideration and study has been given to the anomalous effect of varying air flow on the deterioration of 5P4E, i.e., the maximum in viscosity increase followed by a lessening of lubricant deterioration with increasing air flow. Certainly, the effect is contrary to that normally experienced in oxidation studies and is assumed to be a distinguishing characteristic of either the fluid or the test apparatus, or both.

In the ultimate development of a specific high-temperature oxidation-corrosion test procedure which will be of predictive value, it is apparent that selection of an appropriate test air flow will pose one of the major difficulties. As high-temperature engine test data become available, several test conditions can be more closely identified such as bulk lubricant temperature and the presence of metals. A quantitative assessment of oxygen availability to the engine lubricant system, however, is virtually unobtainable. Even estimates of this variable will not fully eliminate the need for air flow studies in developing the glassware test, since some extrapolation will be necessary in the transition from full-scale system conditions to bench-test operation.

Accordingly, oxidation-corrosion test data were obtained for several lubricants over a wide range of air flow rates. Such data would prove useful in future test development, and in comparing the sensitivity to air rate between various lubricant types. Figure 4 illustrates the results of test series for three radically diverse lubricant formulations: 5P4E polyphenyl ether, experimental oil MLO-62-1005, and a polyol ester, O-60-27. As shown, F-1041 and MLO-62-1005 demonstrated a somewhat similar profile for viscosity increase. O-60-27 indicated no sensitivity at the low air rates such as that shown by the other oil types. A considerable acceleration in deterioration did occur for the ester as air flow was raised from 75 to 130 liters/hr. It will be observed, however, that due to the different performance capabilities of the three fluids, data shown in Figure 4 are not for the same test temperature or time for all oils. Possibly, O-60-27 might follow the trends of the other fluids if test conditions were adjusted to give a higher level of degradation in the low air flow range.

Figures 5 to 8 are graphic presentations of intermediate viscosity data for 48-hr, 425°F runs on four additional lubricants at various air flows. Lubricant O-62-25 is a MIL-L-9236 type fluid similar to O-60-27.

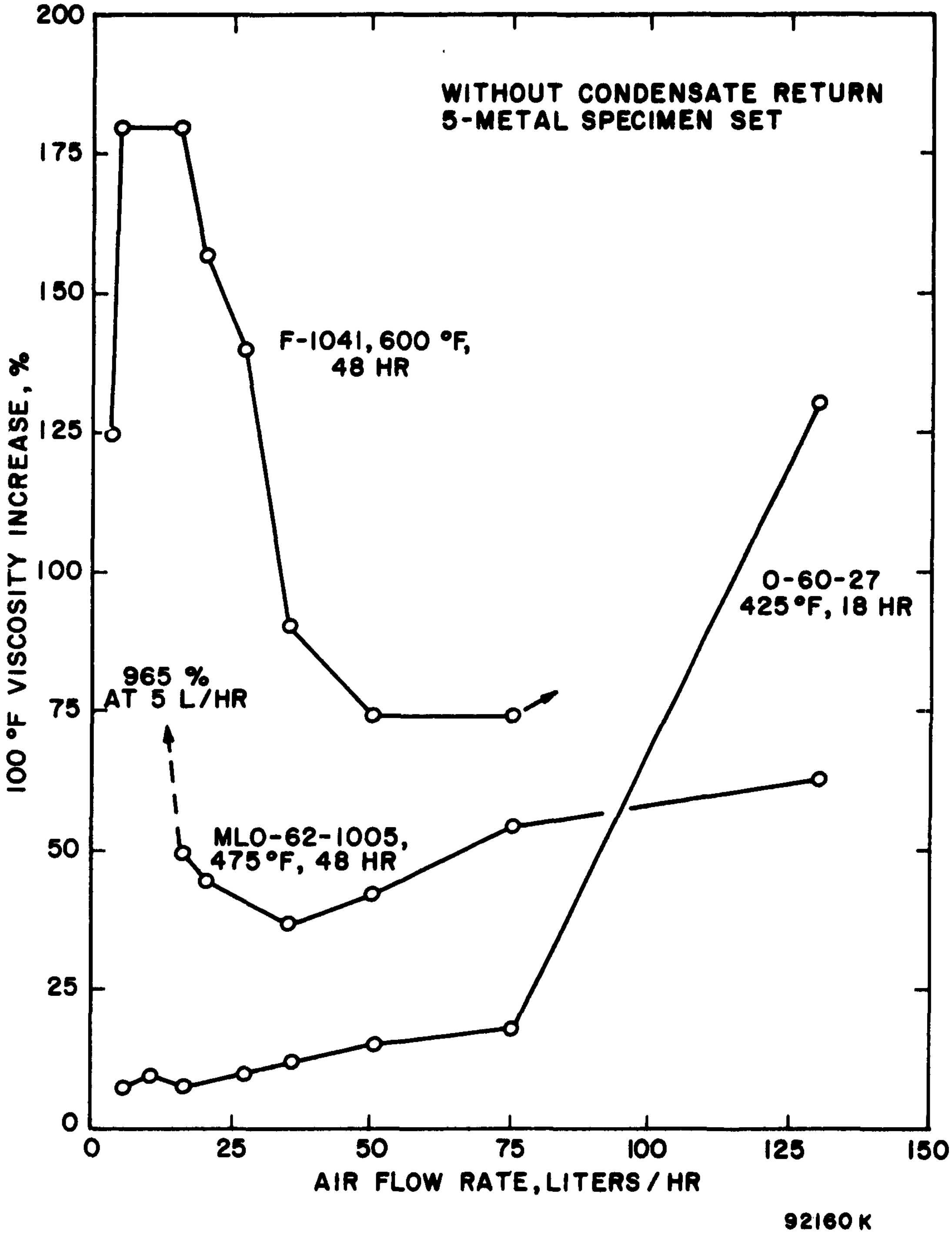

FIGURE 4. EFFECT OF AIR FLOW RATE ON DETERIORATION OF THREE OIL TYPES

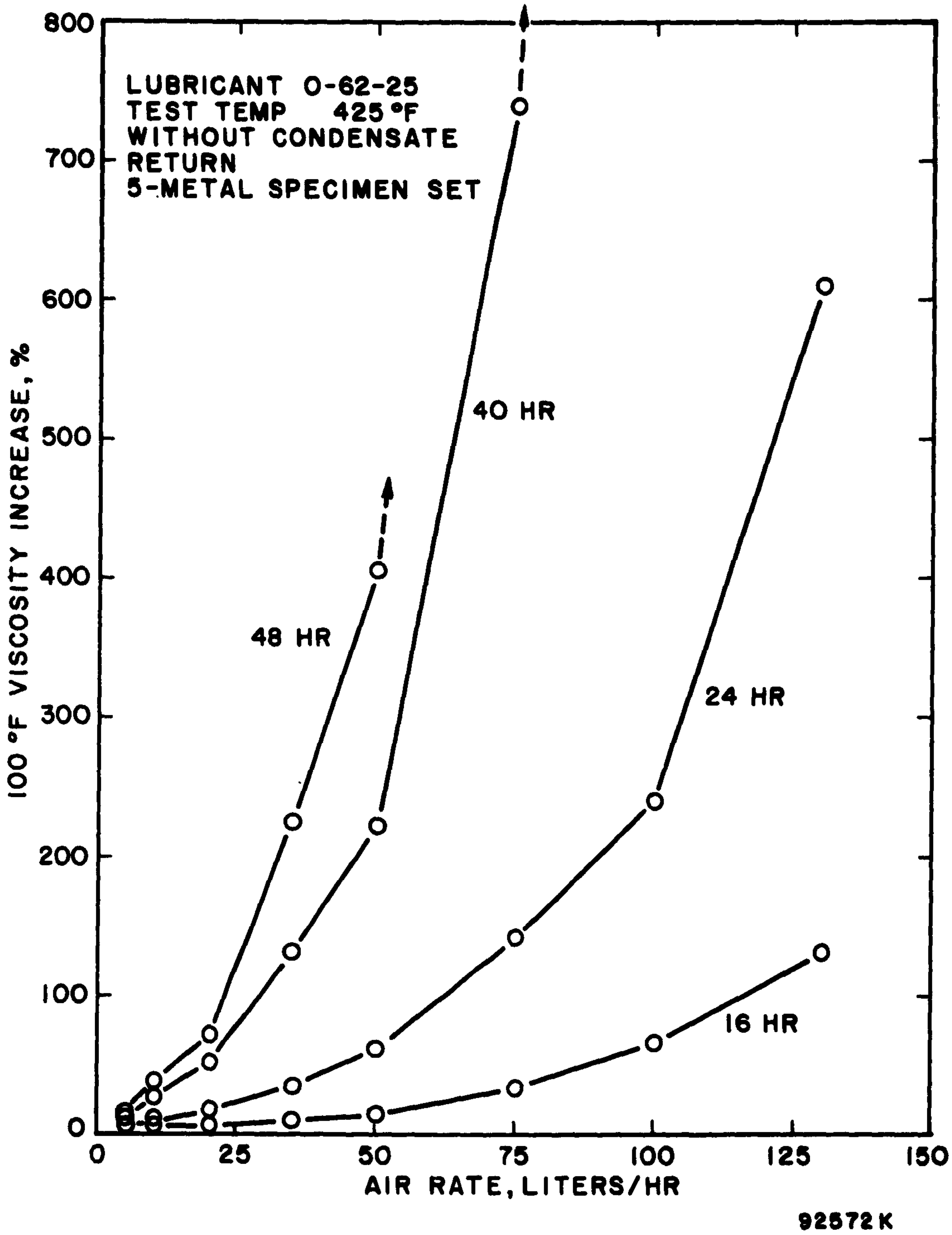

FIGURE 5. EFFECT OF AIR FLOW RATE ON LUBRICANT DETERIORATION OF O-62-25

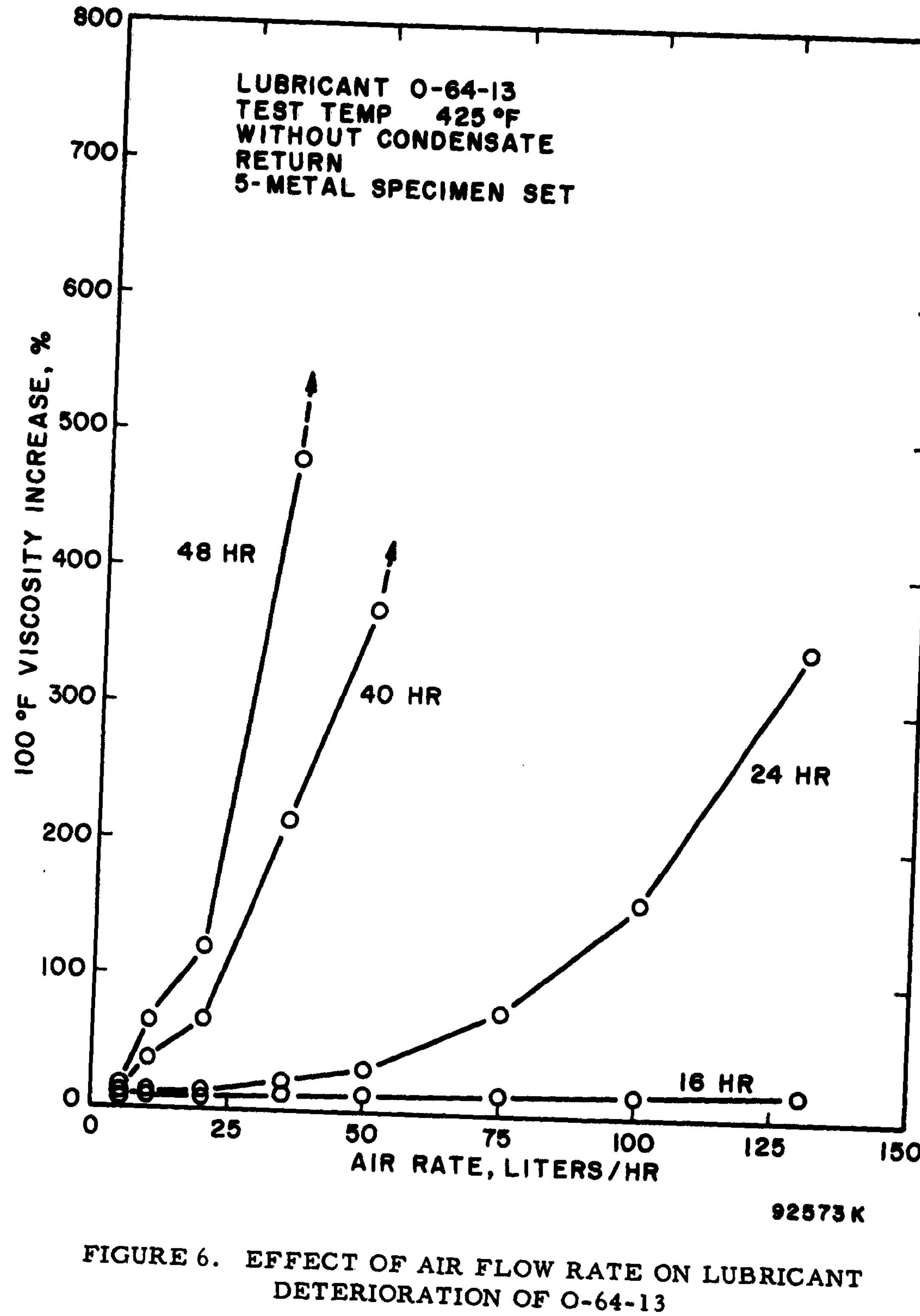

FIGURE 6. EFFECT OF AIR FLOW RATE ON LUBRICANT DETERIORATION OF O-64-13

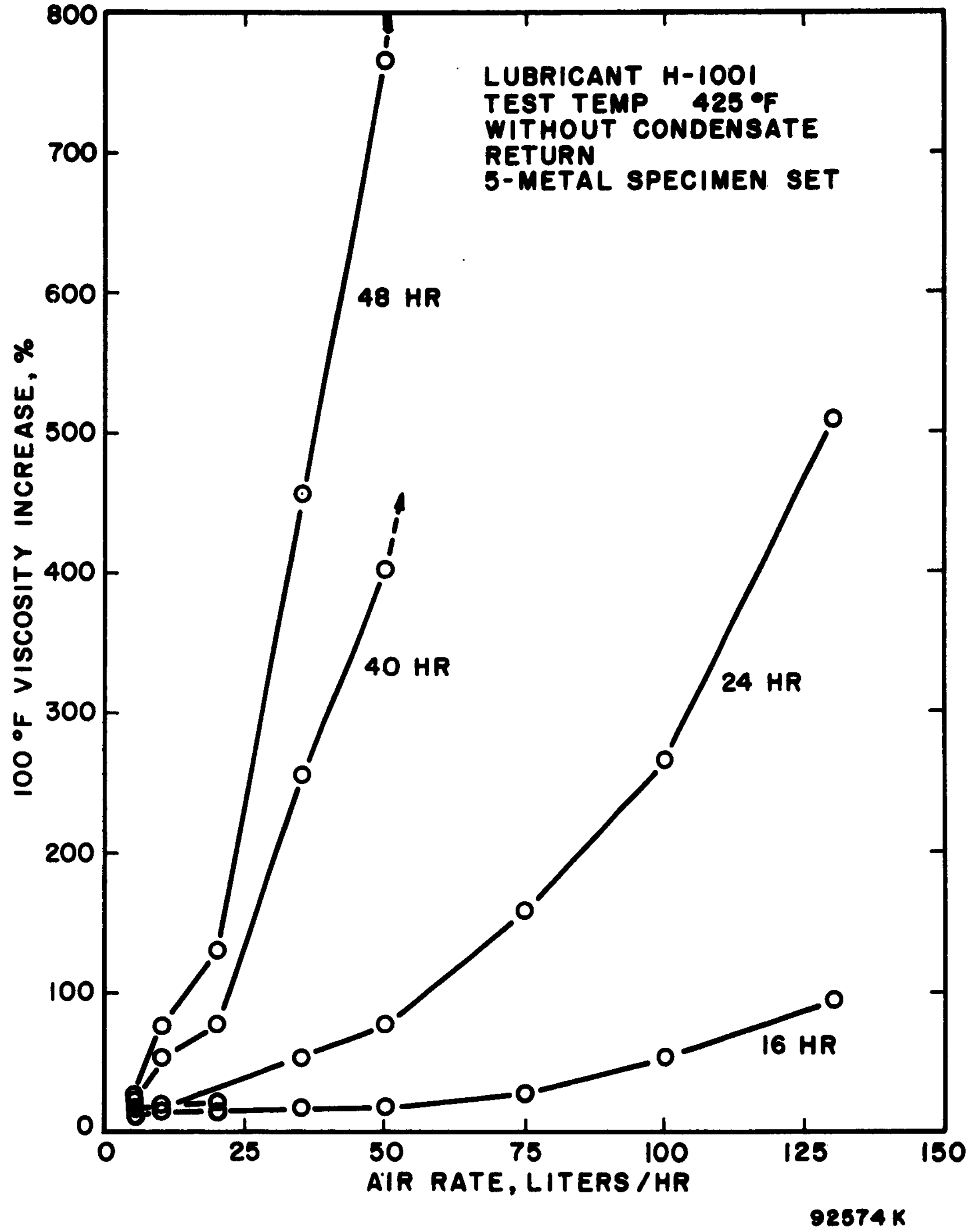

FIGURE 7. EFFECT OF AIR FLOW RATE ON LUBRICANT DETERIORATION OF H-1001

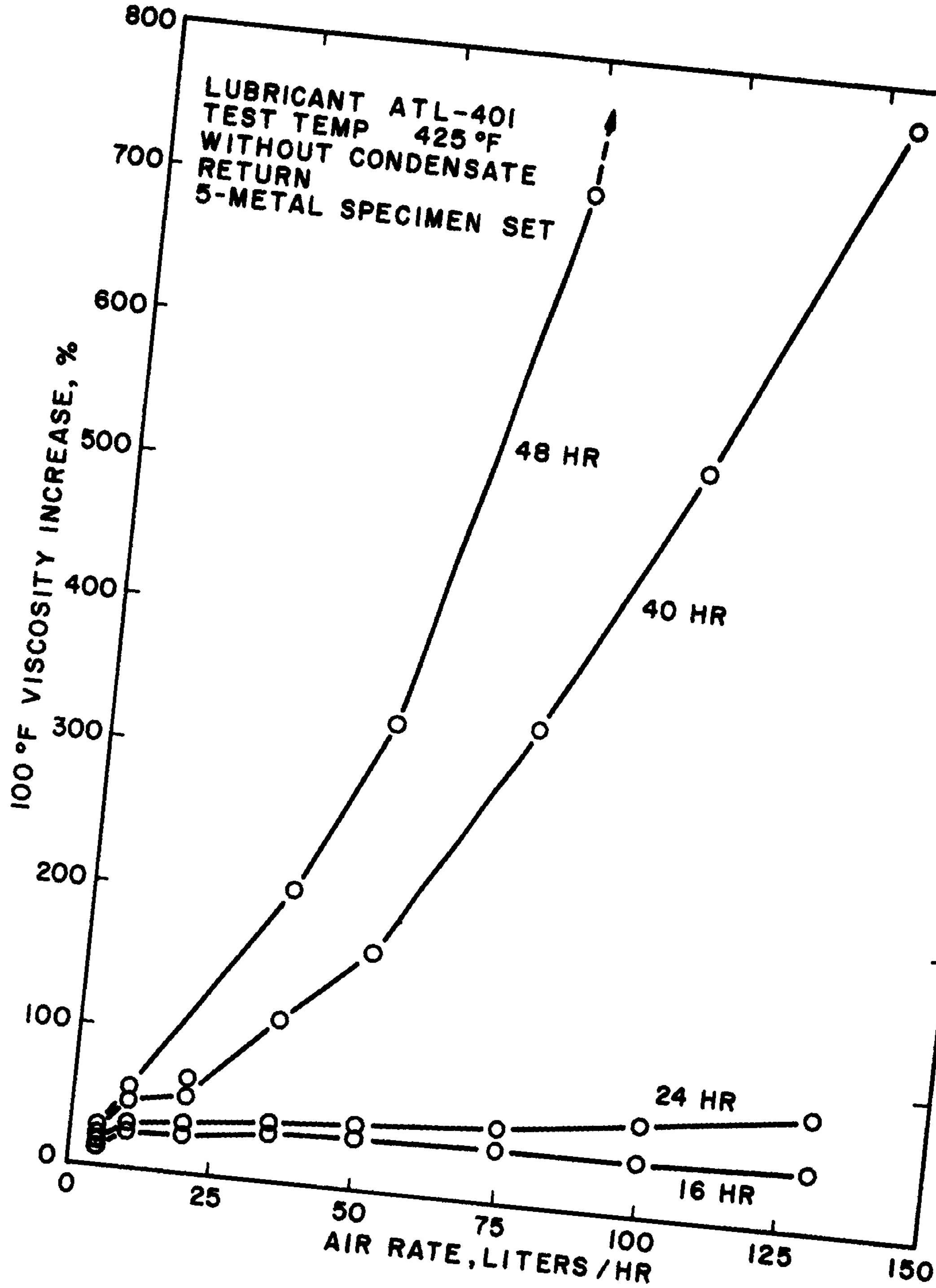

FIGURE 8. EFFECT OF AIR FLOW RATE ON LUBRICANT DETERIORATION OF ATL-401

Lubricants O-64-13, H-1001, and ATL-401 are fluids somewhat more superior than the general MIL-L-9236 class of oils. In general, no unusual effects were noted by performance data for these lubricants. Lubricant deterioration as indicated by viscosity increase followed the normally anticipated trend, i.e., increased degradation with increased air flow.

The oxidation characteristics for the four oils were qualitatively very similar, although ATL-401 (Figure 8) exhibited the highest resistance to deterioration. Each of the lubricants tested underwent accelerated degradation after 24 hr at air rates of 50 liters/hr and above.

D. CRC Oxidation-Corrosion Tests

1. Apparatus and Test Procedures

Pertinent aspects of the two tentative CRC test procedures are listed in Table 34. Method B (except for the presence of copper) is the one hitherto employed in the SwRI program based on satisfactory correlation with engine test results at 425°F. Method A is an alternate procedure selected by the CRC Bench Tests Panel for study and comparison.

The metal specimens are of the same dimensions as those normally employed in the SwRI program: 3/4-in. O.D. by 1/4-in. I.D. by 0.032 in. thick. The specimen washers are stacked directly on the air tube; the first resting on a collar approximately 15 mm from the lower end of the tube. Succeeding specimens are separated by a 1/4-in. glass spacer. The metals are arranged in the order given in Table 34 with aluminum in the lowest position.

The associated test glassware is identical to that originally employed in SwRI tests with the aluminum block except, as noted previously, the test cell head and (where used) the fritted-glass air diffuser.

The test cell head is constructed with a standard-taper 71/60 ground-glass joint on the lower end which mates with the test cell joint. The upper surface of the head is formed in a dome-shaped contour. Attached to this surface are three female, ground-glass joints. A 10/30 joint is centrally located to accommodate the air tube. A second 10/30 joint, slightly offset from center, provides for temperature measurements and intermediate sampling. Offset and at a 90° position from the sampling port, a 24/40 joint is attached to relieve effluent vapors. Using the condensate return procedure (Method A), a 300-mm water-cooled Allihn condenser is directly attached to the latter joint. The nonreflux test procedure employs a connecting arm,

TABLE 34. COMPARISON OF CRC OXIDATION-CORROSION TEST METHODS

	Test Method A		Test Method B
Sample volume, ml	200		200
Air rate, liters/hr	10		130
Test duration, hr	48		48
Condensate return	Yes		No
Intermediate sampling, hr	16, 24, 40		16, 24, 40
Metal specimens	Aluminum	(bottom)	Aluminum
	Silver		Silver
	Copper		Copper
	Mild steel		Mild steel
	Magnesium		Stainless steel
	Titanium	(top)	Titanium

with a 15° downward slant, between the 24/40 head joint and an overboard condenser. The condenser design is optional. For this study, a 200-mm water-cooled Graham condenser was used.

The fritted-glass air diffuser is a 30-mm diameter glass disk (Corning Glass Works No. 39534) centrally attached to a 6-mm glass tube. The fritted portion of the disk, located on the upper surface, is of coarse porosity with a nominal pore size of 40 to 60 microns.

2. Test Results and Discussion

As mentioned earlier, the CRC oxidation-corrosion procedure is being developed as a screening test for the evaluation of advanced turbine lubricants at 500° F. The progress of this development has been somewhat hindered by the nonavailability of lubricants capable of operation at this temperature level. Consequently, some compromise in test temperature was necessary. The results reported herein were obtained with H-1001 at 425° F and with ATL-305 and ATL-401 at 450° F.

Pressure vs air flow measurements were taken on each of the fritted-glass air diffusers prior to use in order to examine the uniformity of air flow and to provide a basis for evaluating the integrity of each diffuser after test. This flow check was continued throughout the test series to make certain that no obviously defective diffusers were used. However, the flow check after test was discontinued since no apparent relationship was found to exist between diffuser pressure values and oxidation-corrosion test data. It was further observed during the early part of this investigation that only a small percentage of the diffusers examined could be reasonably cleaned after use. Therefore, reuse of the diffuser was considered unwise, and all tests were conducted with new diffusers.

The primary objective of this effort was to investigate the advantages and disadvantages of employing the air diffusers rather than the normal open-end air tubes. The test series included three determinations on each lubricant-method-air tube combination. In general, the tests were performed in random order. The three determinations for a given condition were not run in the same 48-hr period, although in some cases two determinations were made simultaneously to expedite testing.

Detailed results using the CRC oxidation-corrosion test procedures are given in Tables 58 to 63 in the Appendix. By interpolation using intermediate sample viscosity results, the following time values illustrate the severity of the method and/or air tube for each of the three lubricants examined:

	Approximate Time to 100% Vis (100°F) Increase, hr			
	Method A		Method B	
	Diffuser	Open	Diffuser	Open
H-1001, 425°F	50	>50	17	32
ATL-305, 450°F	36	42	18	16
ATL-401, 450°F	32	44	18	16

Without exception, Method B (nonreflux) gave higher oxidative deterioration than Method A. Note that a slight extrapolation beyond 48 hr was necessary in the case of H-1001 with Method A. Comparison of air tube types for a given method reveals that the diffuser tests for Method A were somewhat more severe than corresponding determinations with the open tube. A similar relationship for air tube type with Method B was shown for H-1001. However, ATL-305 and ATL-401 indicated a reversal in severity for air tube design with the B procedure.

Of the metal specimens used with the CRC procedures (Table 34), significant metal attack was observed only with copper and magnesium. Individual results are shown in the Appendix for all metals. Average, end-of-test data for the three determinations at each condition are given here for copper and magnesium:

	Average Weight Change, mg/cm^2			
	Method A		Method B	
	Diffuser	Open	Diffuser	Open
H-1001, 425°F				
Copper	-0.1	-0.1	-0.3[a]	-0.4
Magnesium	-17.8	0.0	-	-
ATL-305, 450°F				
Copper	-26.2	-7.6	-6.0	-5.3
Magnesium	(b)	-32.3	-	-
ATL-401, 450°F				
Copper	-16.9	-6.5	-5.8	-4.1
Magnesium	(b)	-30.7	-	-

(a)Test terminated at 40 hr.
(b)Specimen totally destroyed.

Copper corrosion by H-1001 was almost negligible for all conditions. ATL-305 and ATL-401 induced rather excessive weight losses for copper, particularly in Method A diffuser tests. Magnesium, when present, was severely attacked in all cases except the Method A, open air tube determinations with H-1001.

In comparing the performance of the air tube types, there are two factors to be considered, namely, test severity and test repeatability. Test severity is not a basic limiting factor because, depending upon the air tube used, the test duration can be so selected to bring the test severity to any desired level. On the other hand, test repeatability (at the desired test severity level) is very important because any test method, in order to be practical, must have reasonable repeatability. It is therefore of special interest to examine the repeatability of the test data obtained in the present investigation.

As will be seen from Tables 58 to 63 in the Appendix, the 48-hr test data would not be suitable for repeatability evaluation, because severe lubricant degradation was obtained under certain conditions. Thus, after discussion with RTD personnel, it was decided to examine the test repeatability at such test durations that would give a viscosity increase for the test lubricants in the range of 50 to 150 percent. This range of lubricant deterioration is considered of most interest in oxidation-corrosion testing, since it generally defines the regime of lubricant usefulness. Viscosity increase of such magnitude was obtained, for ATL-305 and ATL-401 at 450° F, at a test duration of 40 hr for Method A and 16 hr for Method B. Unfortunately, it was not possible to select intermediate data for H-1001 at 425°F within this viscosity region. For example, using Method B with air diffuser, the 16-hr results for this lubricant gave approximately 22 percent viscosity increase; whereas the 24-hr value indicated marked acceleration of oil deterioration with an increase of over 1000 percent. A run was made at 450° F to determine whether the higher temperature would yield results within the range of interest. At 16 hr however, the H-1001 sample had undergone complete gelation. Thus, the 425° F test data for this oil at 48-hr duration for Method A and 16-hr duration for Method B are used for comparison.

Pertinent summary data on test repeatability using the CRC procedures are given in Tables 35 to 37 for the lubricants mentioned. As illustrated, good test repeatability was demonstrated by the lubricant properties measured. A comparison of end-of-test oil loss results reveals that these values were generally of the same magnitude for both diffuser and open air tubes, with a given test method-lubricant combination. With certain lubricants and test conditions, a particular tube type resulted in a higher loss, e.g., ATL-305 showed greater loss after 48 hr for the diffuser using Method A than corresponding tests with the open tube. This effect was reversed

TABLE 35. SUMMARY OF OXIDATION-CORROSION TEST RESULTS ON H-1001 AT 425°F

Air Tube Type		Viscosity Increase at 100°F, %	Neut. No., mg KOH/g	Oil Loss, wt % at 48 hr
		CRC Test Method A, 48-hr Sample		
Diffuser		76	13.8	4
		96	15.5	4
		82	14.4	5
	Mean	85	14.9	
	Std Dev	10	1.0	
Open		28	3.2	3
		30	3.2	4
		27	3.1	2
	Mean	28	3.2	
	Std Dev	2	0.1	
		CRC Test Method B, 16-hr Sample		
Diffuser[a]		21	0.6	53 (40 hr)
		22	0.6	50 (40 hr)
		23	0.5	50 (40 hr)
	Mean	22	0.6	
	Std Dev	1	0.1	
Open		20	0.6	45
		22	0.6	46
		21	0.6	46
	Mean	21	0.6	
	Std Dev	1	0.0	

(a) Severe lubricant foaming within the test period of about 22 to 24 hr.

TABLE 36. SUMMARY OF OXIDATION-CORROSION TEST RESULTS ON ATL-305 AT 450°F

Air Tube Type		Viscosity Increase at 100°F, %	Neut. No., mg KOH/g	Oil Loss, wt % at 48 hr
	CRC Test Method A, 40-hr Sample			
Diffuser		137	12.0	15
		119	11.7	10
		116	12.3	19
	Mean	124	12.0	
	Std Dev	11	0.3	
Open		98	5.6	6
		88	4.8	3
		72	3.8	5
	Mean	86	4.7	
	Std Dev	13	0.9	
	CRC Test Method B, 16-hr Sample			
Diffuser[a]		93	1.6	54
		91	1.5	37 (40 hr)
		86	1.5	51
	Mean	90	1.5	
	Std Dev	4	0.1	
Open		99	1.3	59
		105	1.4	61
		101	1.4	59
	Mean	102	1.4	
	Std	3	0.1	

(a) Severe lubricant foaming after 1 hr, continuing until the end of test.

TABLE 37. SUMMARY OF OXIDATION-CORROSION TEST RESULTS ON ATL-401 AT 450°F

Air Tube Type		Viscosity Increase at 100°F, %	Neut. No., mg KOH/g	Oil Loss, wt % at 48 hr
	CRC Test Method A, 40-hr Sample			
Diffuser		138	9.3	15
		161	10.4	19
		167	5.1	19
	Mean	155	8.3	
	Std Dev	20	2.8	
Open		89	4.9	9
		61	3.9	7
		80	5.6	8
	Mean	77	4.8	
	Std Dev	14	0.9	
	CRC Test Method B, 16-hr Sample			
Diffuser(a)		82	1.2	49
		90	1.9	52
		88	1.6	52
	Mean	87	1.6	
	Std Dev	4	0.4	
Open		96	1.4	58
		106	1.9	58
		109	2.1	61
	Mean	104	1.8	
	Std Dev	7	0.4	

(a) Severe lubricant foaming after 1 hr, continuing until the end of test.

using Method B with ATL-305. In each case, the higher oil loss, irrespective of air tube type, was associated with an increased level of lubricant degradation at 48 hr.

Standard deviations for viscosity increase and neutralization number data at each test condition were calculated for the triplicate determinations as listed in Tables 35 to 37. The viscosity increase data are shown graphically in Figure 9. The deviations remained relatively low in all cases with no apparent advantage exhibited by either air tube type. The largest spread in standard deviation for tube type occurred with H-1001 using Method A: the open-end tube data showed a standard deviation of 2 percent while the diffuser test data gave a standard deviation of 10 percent. This difference is not considered excessive, however, particularly since the diffuser tests were at a much higher level of oxidative degradation.

With respect to test procedure, however, examination of the viscosity data shown in Figure 9 would suggest an advantage in test repeatability for Method B. Standard deviations of viscosity increase were 7 percent or below with this procedure, whereas the values for Method A were generally greater than 10 percent. It is felt that this significant difference in repeatability may be due primarily to the large difference in the sample times used for the evaluation. Method A results were taken at 40 or 48 hr; Method B data, because of increased test severity, utilized the 16-hr sample. Thus, any minor variations in the conduct of the test would be magnified in the case of Method A.

A serious discrepancy in the operation of the Method A (reflux) diffuser tests was encountered in the later stages of this program. A significant drop in sample temperature was noted with H-1001 and ATL-401 in these tests. The CRC glassware provides for the insertion of a glass-encased thermocouple through the test cell head into the lubricant sample. Upon test start-up, the sample temperatures are noted and the aluminum block is set to control at the mean reading of the test samples. For example, a 450°F test with the SwRI apparatus requires an aluminum block temperature of 451 to 452°F to maintain a true 450°F test sample temperature. The test is normally run unattended overnight, and, until noting the aforementioned phenomenon, there was no need for continuous recording of individual sample temperatures. Thus, after the initial control setting, only spot-check readings were taken.

The sample temperature drop in Method A diffuser tests at 450°F was first observed with ATL-401, after the test series on ATL-305 had been completed. At 40 hr, the test cells with ATL-401 indicated a lubricant sample temperature of approximately 447°F. This reading continued a gradual

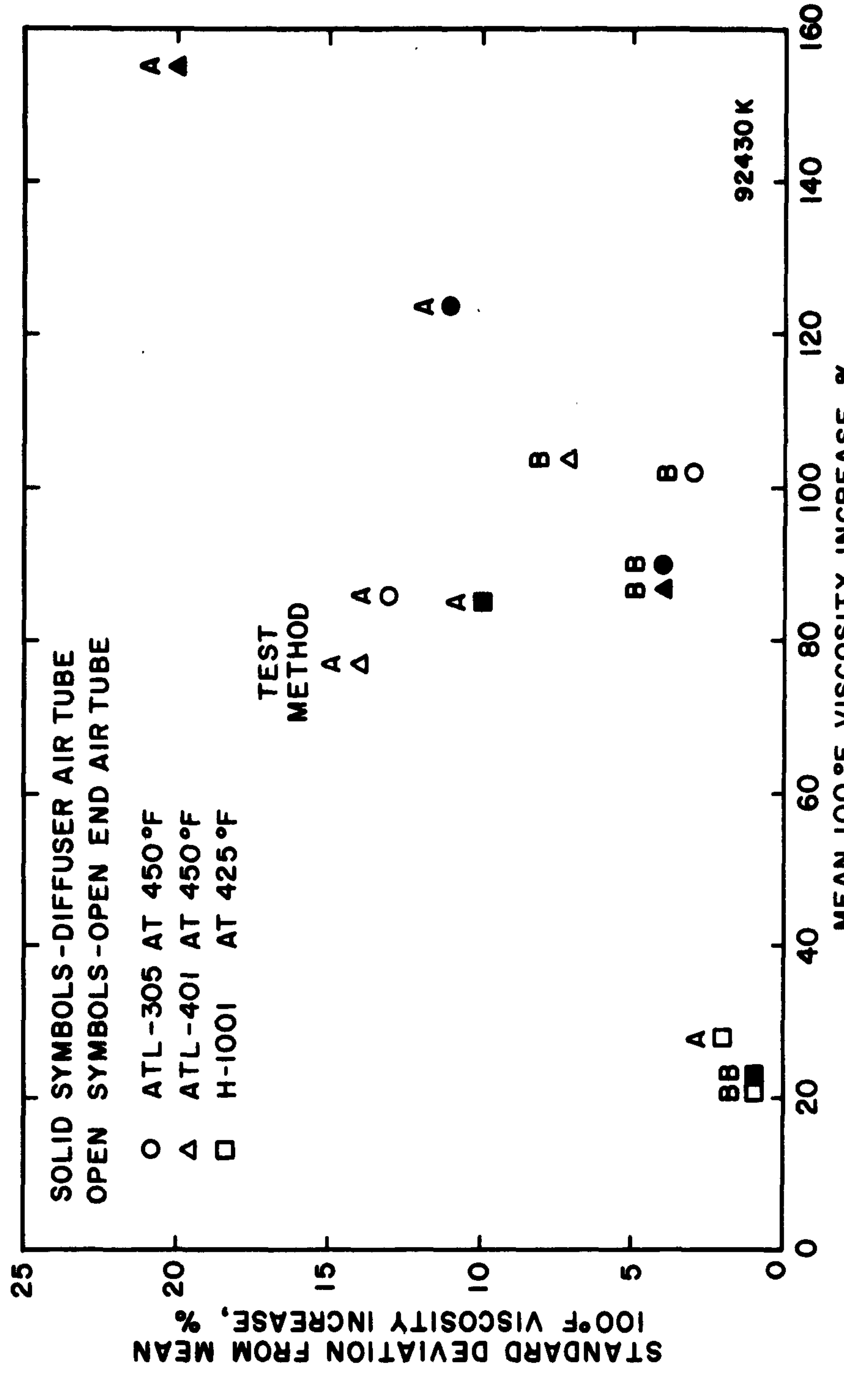

FIGURE 9. REPEATABILITY OF CRC OXIDATION-CORROSION TEST VISCOSITY RESULTS

decline until the end of test (48 hr) at which time a reading of 440° F was noted. The phenomenon was associated with, and undoubtedly caused by, rapid and violent refluxing of condensable vapors by the water-cooled condenser. The 425° F tests with H-1001 under similar conditions showed a sample temperature of about 423° F at 40 hr. This value reached a minimum of 420° F at 44 hr. At this time the observed refluxing began to subside, and at 46 hr lubricant sample temperature returned to 425° F for the test duration.

Adjacent test cells being run under different conditions were not affected by the described temperature discrepancy in either the ATL-401 or H-1001 tests. For this reason, it was not possible to overcome the sample temperature descent by increasing the block temperature.

In order to obtain a more complete temperature profile of the phenomenon, the test apparatus was instrumented to allow for continuous recording of test sample temperature, and repeat Method A diffuser tests were performed on each of the three lubricants used in the program.

Figure 10 presents a graphic illustration of the time-temperature data throughout the 48-hr test period. Temperature readings at 30-minute intervals are plotted in the figure except for certain maxima or minima which occurred in a time interval of less than 30 minutes and are thus shown by intermediate points. Lubricants ATL-305 and ATL-401 underwent a sample temperature decline after about 4 hr of test time. It should be noted that both oils indicated a return to the 450° F control temperature during the intermediate sampling process at 16 hr and at 24 hr. As previously noted, the drop in sample temperature was associated with a rapid and violent refluxing of condensable vapors by the water-cooled condenser. This phenomenon was interrupted by the withdrawal of the intermediate sample in most instances, and lubricant temperature generally returned to the control temperature for a brief period. ATL-401 sample temperature ceased its fluctuation at about 31 hr and held at 450° F for the remainder of the test. In contrast, ATL-305 indicated a general temperature decline after 24 hr, reaching a minimum of 423° F just prior to test termination.

Temperature data for the Method A diffuser test with H-1001 indicated no variation until about 38 hr, as shown in Figure 10. Sample temperature returned to the 425° F control temperature when the 40-hr sample was withdrawn. At approximately 43 hr, the H-1001 lubricant experienced a temperature drop of about 4° F within the test period of 42 to 43.5 hr. No further temperature variation occurred after this time.

Lubricant viscosity and neutralization number data for the aforementioned tests indicated very good repeatability with previous results.

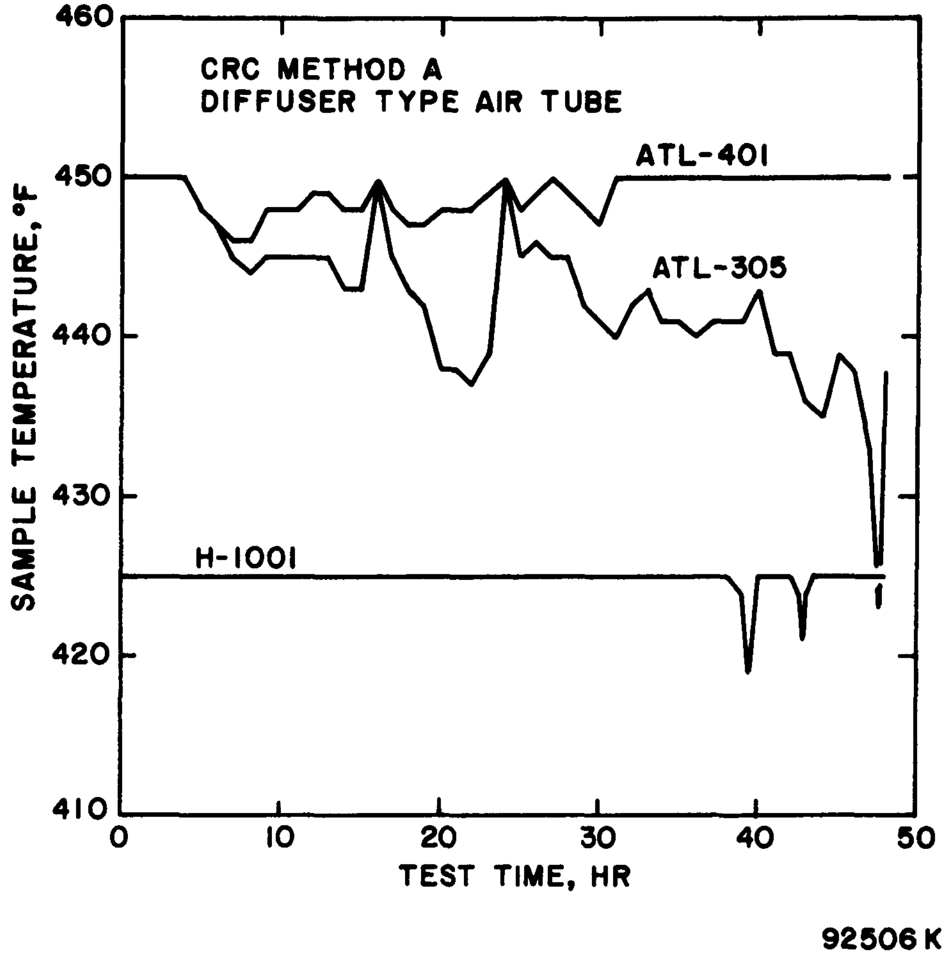

FIGURE 10. TIME-TEMPERATURE PLOT FOR CRC METHOD A DIFFUSER TESTS

However, sample temperature variation did not precisely correspond to the trends which were noted earlier. For example, spot-check readings on one test with ATL-401 revealed a sample temperature ranging from 447 to 440°F during the test period of 40 to 48 hr. The data of Figure 10 show no such effect at that time period for this particular run.

As mentioned earlier, a major consideration in using fritted-glass disks in the CRC oxidation-corrosion test was to provide highly dispersed air resulting in a more uniform air-to-metal contact. It was theorized that the relatively large-bubble air stream produced by the open-end tube might give misleading corrosion data with respect to specimen position on the stack. It was reasoned that a valid evaluation of this concept could be obtained in tests using a single metal specimen type in all six coupon positions. Thus, any variation in metal attack throughout the specimen stack would be readily apparent.

Table 38 lists the results of two determinations of this type using copper with ATL-305. Method B was the procedure used. The tests were terminated at 16 hr to avoid the possibility of uncovering the upper specimens by oil loss and intermediate sampling. It is seen that both air tube types demonstrated uniform corrosion for all positions, although the diffuser showed an overall higher attack of copper than the open tube. The diffuser test gave the largest spread in weight loss (1.4 to 1.9 mg/cm^2); however, the variation is estimated to be comparable to the overall precision of the specimen weighing procedure.

The results of additional tests of this nature are given in Table 39 using a 5P4E polyphenyl ether lubricant (F-1041) with both CRC methods. Once again no significant variation in metal attack occurred for a given specimen set. There was a distinct difference noted in the type of copper attack between the two procedures. The reflux procedure (Method A) gave weight losses of about 1.0 mg/cm^2; whereas, the nonreflux tests resulted in slight specimen weight gains. In the latter case, a hard, light grey deposit was uniformly distributed over the specimen surface.

In completing this study, one test series was performed with ATL-401 using an all-copper or all-magnesium specimen set. These results are given in Table 40. With this lubricant, noticeably inconsistent metal corrosion occurred in Method A diffuser tests with copper. A significant copper weight loss was obtained for all specimen positions; however, the bottom specimen in the Method A diffuser test sustained a loss of more than double that for the upper specimens. A less significant variation in metal attack was noted in the Method A diffuser test with magnesium. The bottom specimen showed no weight change, and the top specimen indicated a weight

TABLE 38. EFFECT OF AIR DISPERSION ON METAL SPECIMEN CORROSION WITH ATL-305

Specimen Position	Copper Weight Change, mg/cm^2	
	Diffuser	Open
1 (top)	-1.5	-1.0
2	-1.4	-1.0
3	-1.5	-1.0
4	-1.6	-0.9
5	-1.7	-0.8
6 (bottom)	-1.9	-1.0

CRC Test Method B.
Test temperature 450°F
Test duration 16 hr

TABLE 39. EFFECT OF AIR DISPERSION ON METAL SPECIMEN CORROSION WITH F-1041

Specimen Position	Copper Weight Change, mg/cm^2			
	CRC Method A		CRC Method B	
	Diffuser	Open	Diffuser	Open
1 (top)	-1.1	-1.1	+0.2	+0.1
2	-1.1	-0.8	+0.3	+0.2
3	-1.1	-0.8	+0.3	+0.2
4	-1.0	-0.7	+0.3	+0.2
5	-1.0	-0.8	+0.2	+0.2
6 (bottom)	-1.0	-0.9	+0.2	+0.2

Test temperature 600°F
Test duration 16 hr

TABLE 40. EFFECT OF AIR DISPERSION ON METAL SPECIMEN CORROSION WITH ATL-401

Specimen Position	Metal Weight Change, mg/cm^2							
	CRC Method A				CRC Method B			
	Diffuser		Open		Diffuser		Open	
	Cu	Mg	Cu	Mg	Cu	Mg	Cu	Mg
1 (top)	-1.5	+0.2	-0.4	-0.2	-1.6	+0.1	-1.1	-0.1
2	-1.7	-0.2	-0.3	-0.3	-1.5	+0.1	-1.1	-0.1
3	-1.6	-0.4	-0.3	-0.2	-1.5	+0.1	-1.1	0.0
4	-1.6	-0.3	-0.3	-0.3	-1.5	+0.1	-1.0	0.0
5	-1.9	-0.4	-0.4	-0.3	-1.5	0.0	-1.0	0.0
6 (bottom)	-3.9	0.0	-0.4	-0.2	-1.7	0.0	-1.1	0.0

Test temperature 450°F
Test duration 16 hr

gain of 0.2 mg/cm^2. In contrast, all of the intermediate magnesium specimens underwent a weight loss ranging from 0.2 to 0.4 mg/cm^2.

Since the aforementioned (single) determinations were the only case in which a variation in metal corrosion occurred, it was decided to obtain repeat data using copper in order to confirm the observed effect. The weight losses are shown here for the repeat run and also the Method A diffuser test listed in Table 40:

Specimen Position	Copper Weight Change, mg/cm^2	
	Test No. 91	Test No. 92
1 (top)	-1.5	-1.4
2	-1.7	-0.6
3	-1.6	-1.7
4	-1.6	-2.1
5	-1.9	-2.0
6 (bottom)	-3.9	-4.1

The same pattern of metal attack was obtained in the repeat run (Test 92) as previously observed. In general, the results indicated good repeatability for specimen weight loss except for the No. 2 position.

E. 10-Hr Modified Oxidation-Corrosion Test

Initial oxidation-corrosion test evaluations on advanced turbine lubricant candidates were usually accomplished by means of the standard 18-hr test using increased temperature increments. This procedure was originally developed to provide correlation with 425°F engine tests of 100-hr duration.

Attempts to utilize 18-hr test data to predict lubricant oxidative performance in the bearing deposits and degradation test (discussed in the following chapter) proved unsuccessful for several reasons. Comparison of results at a given test temperature and time reveal that lubricant deterioration, as indicated by sample viscosity increase, is much more severe in the glassware test than the bearing test. This may be attributed chiefly to the large difference between the two tests in air flow rate per unit volume of oil and, probably to a lesser extent, the practice of oil make-up in the bearing test. Attempts at correlation with present data are further complicated by the bearing test

procedure whereby the lubricant charge is replaced after reaching a 100 percent viscosity increase. In addition, it should be noted that the air moisture content differs between the two tests. The normal oxidation-corrosion test procedure employs dry air, whereas the bearing test utilizes air which is nominally water-saturated. As discussed earlier, the use of moist air showed a significant effect on oxidation-corrosion test results, dependent upon lubricant type and test temperature.

Thus, it was apparent that in order to attain correlation, the oxidation-corrosion test procedure would require some modification to conform with bearing test conditions affecting lubricant degradation. Using the basic 18-hr test procedure and apparatus, a modified oxidation-corrosion test was formulated by adjusting the test conditions of time and air flow rate. It should be emphasized that the sole purpose of this work was to devise a correlative test which would thereby aid in the selection of bearing test temperature conditions.

The selection of air flow rate for the modified oxidation-corrosion test was based on a proportionality for lubricant sample volume. In most cases, the bearing rig is operated without air to the test oil sump using a 2-gallon oil charge. Air flow to the bearing machine end-cover is 0.35 cfm. Because of the action of the screw-thread seal, it is assumed that the total air flow to the machine is removed by the test-oil scavenge pump and bubbled through the sump. On the basis of this assumption, 0.35 cfm (10 liters/min) air per 2-gallon sample would correspond to an oxidation-corrosion test air rate of 16 liters/hr for the normal 200-ml sample. However, an additional source of air is believed to influence lubricant deterioration in the bearing test. The axial pumping action of the screw-thread seal causes a rather large volume of air to be drawn into the bearing head at the two exterior seal vents. Measurements of this air flow during test indicate a total flow into the head of about 12 liters/min (6 liters/min/vent). Since the absolute pressures of the bearing test section and the support section differ by only 0.3 to 0.4 in. of water, it is assumed that the seal-vent air is about equally divided between the two chambers. To account for this additional air flow, a total oxidation-corrosion test air rate of 25 liters/hr would be required.

Because of the bearing test oil change requirement, it was felt that the predictive value of the oxidation-corrosion test should be evaluated in relation to 16-hr bearing test viscosity results. This time period is of most interest since an oil change prior to 16 hr is considered as unsatisfactory lubricant performance on the basis of present bearing test criteria.

On the basis of the foregoing considerations, a modified oxidation-corrosion test was conducted at 25 liters/hr dry air flow to establish the test duration necessary for correlation with 16-hr bearing test viscosity

results. Lubricant H-1001 was used since extensive bearing test data were available for this fluid. An intermediate sampling procedure revealed that the desired level of lubricant deterioration was attained at 10 hr. Additional fluids were subsequently evaluated with the 10-hr oxidation-corrosion test using both dry and moist air. Since moist air is used in the bearing test, it appeared desirable to obtain results for both air conditions.

A comparison of viscosity results for the 10-hr oxidation-corrosion test and the bearing test is presented in Table 41. For the lubricants and test conditions examined in this correlation study, there was essentially no effect exhibited by the use of moist air in the oxidation-corrosion test. Consequently, the determinations were considered as duplicate tests, and the average values were used in Figure 11, which illustrates the degree of correlation of the 10-hr oxidation-corrosion test data with the bearing test viscosity data. Reasonable correlation is indicated in Figure 11 by a line placed to conform with four of the six oils selected for this study. However, ATL-304 and ATL-403 (points 7 and 8 of the figure) showed virtually no correspondence of results between the two tests. As shown in Table 41, ATL-403 was evaluated with the 10-hr test in a step-temperature sequence. These data would suggest a lubricant temperature capability in the bearing rig of 575°F, or higher. The subsequent bearing test, however, indicated that the maximum temperature capability of the fluid is 500°F.

Thus, it is apparent that the 10-hr oxidation-corrosion test procedure would require further modification to be of value in the program. It is felt that the basic approach used in this effort was sound. However, insufficient information exists to perform exacting extrapolations for air flow rate between the bearing test and the oxidation-corrosion test.

F. Conclusions

Analysis of 425°F 18-hr test data between the oil bath and the aluminum block apparatus showed very good correspondence for results when operated at the same sample temperature. Consequently, virtually all work on this phase was confined to the use of the aluminum block equipment.

A total of 18 high-temperature lubricant candidates were evaluated in an 18-hr 425 to 500°F oxidation-corrosion test program. Of these 18 fluids, six failed at 425°F, seven were unsatisfactory at 450°F, and three failed at 475°F. Only two lubricants, ATL-403 and O-64-17, warranted evaluation at 500°F; however, both were unsatisfactory at that temperature.

The 18-hr procedure was also employed at 425°F using moist air in tests on several MIL-L-9236 type oils. The use of air with a nominal relative humidity of 100 percent served to improve performance for all lubricants

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TABLE 41. COMPARISON OF 10-HR MODIFIED OXIDATION-CORROSION TEST RESULTS AND BEARING TEST DATA

Oil Code	Bearing Test Data: Temp, °F, Sump/Bearing	Bearing Test Data: 100°F Vis Incr, % at 16 hr	10-hr Modified Oxidation-Corrosion Test Data[a]: Test Temp, °F	100°F Vis Incr, %: Dry Air	100°F Vis Incr, %: Wet Air
H-1001	475/525	46	475	51	48
	500/550	69	500	67	63
	525/575	~95[b]	525	82	83
O-62-25	450/475	25	450	20	16
ATL-304	500/550	92	500	36	43
ATL-401	475/575	60	475	40	40
ATL-402	500/550	53	500	34	30
	525/575	77	525	45	54
ATL-403	500/550	96	500	26	25
			525	32	32
			550	51	45
			575	78	77

(a) Test conditions: Sample vol 200 ml
Air rate 25 liters/hr
5-metal specimen set
Without condensate return

(b) Average value for six tests. Value is approximated since one test required an oil change at 14 hr.

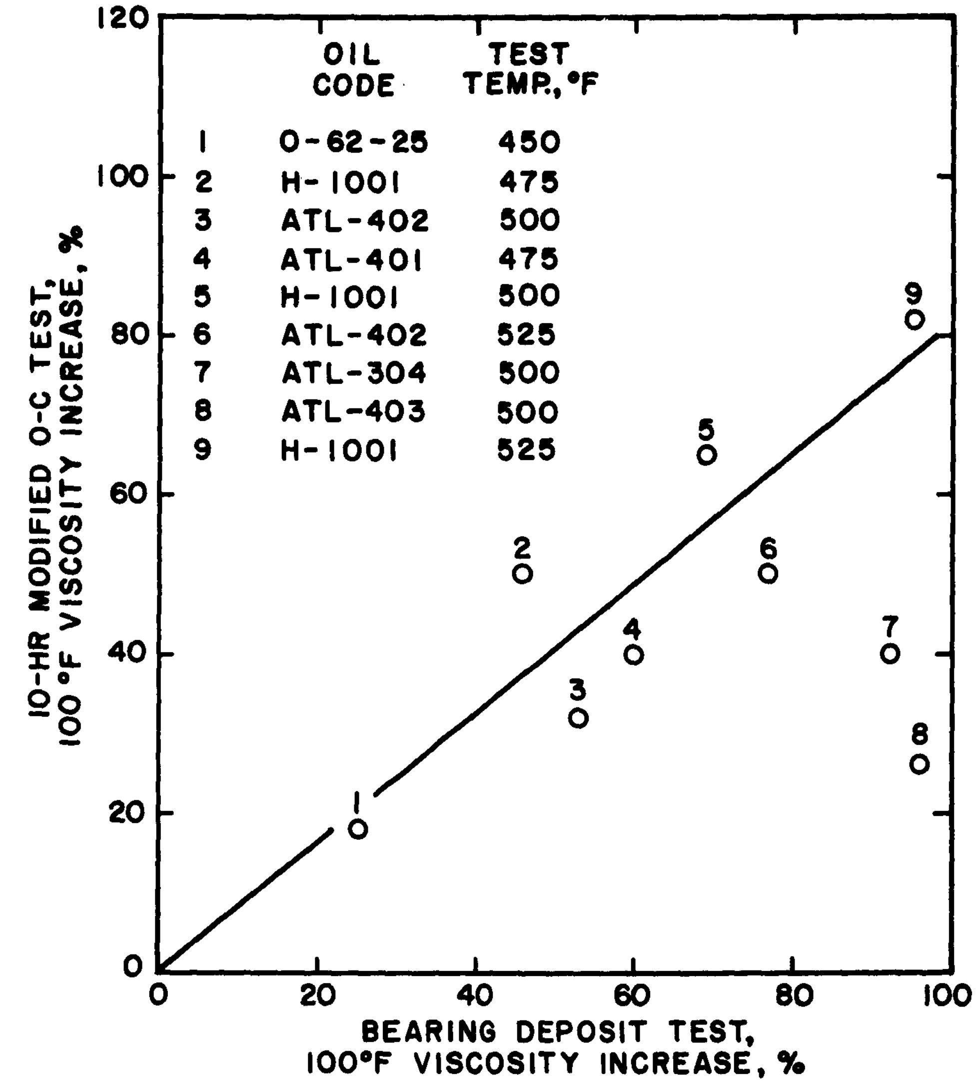

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FIGURE 11. CORRELATION OF VISCOSITY RESULTS, 10-HR MODIFIED OXIDATION-CORROSION TEST VS 16-HR BEARING DEPOSIT TEST SAMPLES

which had undergone significant deterioration using dry air. Two lubricants from this group were subsequently tested with air of 50 percent RH. Results indicated almost no difference for moisture between 50 and 100 percent RH data. Further studies with other lubricant types on the effect of water-saturated air in the 18-hr test revealed that viscosity data were significantly affected in some cases. The effect was not consistent for all lubricants evaluated and, in the case of certain oils, was dependent upon test temperature.

Studies with 5P4E polyphenyl ether (F-1041) indicated moderate lubricant degradation at 550°F, with little or no effect shown for varying air flow or condensate return. Substantial deterioration occurred at 600 and 650°F with 5P4E. At 600°F sample temperature, a significant effect was noted for air flow rate, with a maximum in oil deterioration encountered within the range of air flow studied. A similar performance trend was obtained with or without condensate return. A much higher level of lubricant degradation was observed in the former case, however. The 650°F test series gave extensive breakdown of the 5P4E fluid. Due to gelation of the material, the maximum test period possible for sample analysis was 24 hr at this temperature. Results obtained at 650°F with condensate return demonstrated rapid and consistent oil deterioration as air flow was increased, with no evidence of a maximum for viscosity increase such as that observed for other test series.

The 600°F test studies with 5P4E using nitrogen-air mixtures showed a relationship between oxidative deterioration, total gas flow rate, and oxygen content of the gas. Although extensive data were not obtained, test results indicated a substantial effect for gas flow rate at relatively high oxygen concentrations. With an oxygen content of 10 percent or less, the influence of gas flow rate was nil.

Investigations at 600°F with 5P4E using various glass condensers indicated a pronounced effect for the efficiency of the condensate return process. Results at two selected air flows showed that 5P4E deterioration was significantly accelerated at condenser efficiencies of 50 percent or more.

Examination of the influence on 5P4E performance of metal test specimens revealed lubricant deterioration was markedly suppressed when copper and magnesium were added to the usual five-metal group (Al, Ti, Ag, steel, stainless steel). This effect was attributed to the presence of copper which appears to inhibit 5P4E oxidation.

Significant metal corrosion for 5P4E at 650°F was consistently obtained with the copper specimen. Although silver corrosion was noted in a few tests, no general relationship was apparent for silver attack and oil performance.

An evaluation of existent correlation between the high-temperature oxidation-corrosion test and 100-mm bearing test results with 5P4E showed excellent correspondence of data except for the 650°F condition with condensate return. It is believed that this discrepancy may be attributed to inherent differences between the two tests with respect to the condensate return process.

Test results with experimental oil MLO-62-1005 revealed that satisfactory oil performance, dependent on air rate, could be expected for a 48-hr test period at 475°F. The lubricant showed severe deterioration, however, at the lowest air flow tested (5 liters/hr) with extensive corrosion of the mild steel specimen.

High-temperature oxidation-corrosion test results on ATL-307 indicated excellent oxidation stability in the temperature range of 500 to 600°F. However, significant metal corrosion was observed with the fluid at sample temperatures of 550 and 600°F. Titanium was the most severely attacked of the metals present.

Test series to examine the influence of air flow rate were carried out for several lubricants included in this program. Experimental oil MLO-62-1005 showed an effect similar in nature to that for 5P4E, i.e., lessened deterioration at increased air rates. The remaining fluids in this study, including two MIL-L-9236 lubricants, exhibited no unusual effect over an air flow range of 5 to 130 liters/hr.

A test series was completed with three lubricants in an examination of various aspects of the CRC oxidation-corrosion test procedures. A comparison of the two procedures showed that the nonreflux method (Method B) gave higher oxidative degradation (for same test duration) than the reflux test procedure for all lubricants tested. Of the metals included in the CRC procedures, significant attack was obtained only with copper and magnesium. Measurable copper weight losses were recorded for all tests with ATL-305 and ATL-401. Values for H-1001 were negligible for the copper specimen. Magnesium, which is present only in the Method A procedure, indicated severe corrosion in all cases except the H-1001 open air tube runs.

Satisfactory test repeatability was obtained for all determinations using both CRC procedures, with Method B slightly superior. Present data comparing the open-end air tube and the fritted-glass disk indicate no marked advantage or disadvantage with respect to test repeatability for either tube configuration.

One detrimental aspect related with use of the diffuser was observed in Method A (reflux) tests. As a consequence of accelerated fluid refluxing, a significant cooling effect was noted in the test sample temperature. Recorded sample temperature measurements on three lubricants under test revealed that significant, uncontrollable cooling of the sample can occur with this procedure. The cooling effect was erratic with respect to test time and differed significantly among the lubricants examined. In addition, tests with the CRC procedures showed a notable variation in metal specimen corrosion with ATL-401 under certain conditions. Method A diffuser tests using an all-copper specimen set indicated a higher weight loss for the bottom specimen than that for the upper five specimens. A similar determination with six magnesium specimens indicated the bottom and top coupons were not as severely corroded as the intermediate specimens.

A 10-hr modified oxidation-corrosion test was used in an attempt to obtain correlation with 16-hr bearing test viscosity data. Reasonable correlation was indicated for four of the six lubricants investigated. However, the remaining two, ATL-304 and ATL-403, showed unsatisfactory correlation.

III. LUBRICANT DEPOSITS AND DEGRADATION

A. General Remarks

The objectives of the lubricant deposits and degradation phase of the program were to develop apparatus and techniques for determining the deposits and degradation characteristics of high-temperature gas turbine lubricants and the evaluation of candidate lubricants under environmental conditions representative of Mach 2.5 to 3 class gas turbine engine designs.

By necessity, therefore, research effort began with the design and fabrication of suitable test equipment followed by the establishment of specific techniques to be employed in candidate lubricant evaluation. This facet of the program received considerable attention and scrutinization inasmuch as the results to be generated would be dependent upon the apparatus developed and the techniques established. A thorough, detailed account of this portion of the work has been previously presented[1], and in essence, has remained unchanged. In general, the Erdco 100-mm roller bearing machine[1] comprised the basic equipment. A special test oil system[1] was designed and utilized in order to meet the program requirements. The test procedure[1] adopted for this study was patterned after that employed in previous studies of this type, but with modifications appropriate to this study. Such additions and modifications found desirable as the work developed, and later incorporated into the test program, are discussed subsequently.

During the period covered by this report, actual investigation into the deposits and degradation characteristics of high-temperature candidate lubricants began with lubricant F-1041, a 5P4E polyphenyl ether. Extensive testing with F-1041, embracing a wide range of test conditions, was conducted in order to provide a baseline performance profile for F-1041. This would permit a comparison of the performance of other candidate lubricants to that of the polyphenyl ether at similar operating environments.

The F-1041 investigation was followed by the evaluation of eleven candidate lubricants at various temperature and air flow conditions. The extent of investigation of a given lubricant was determined primarily by its temperature capability and availability. In addition, selected lubricants were utilized in periodic, repeat tests which allowed a running check of test machine bias and test repeatability. The results of these tests were conclusive in establishing reliability of test precision throughout the study and in successfully screening candidate lubricants on the basis of their temperature-deposits-degradation behavior.

B. Test Equipment

1. Erdco 100-mm Roller Bearing Machine

Two standard Erdco 100-mm roller bearing machines, previously described[1], were employed in the investigation herein reported. No changes or modifications were effected with respect to design, operating principle, or instrumentation in the performance of this work.

2. Drive Stand

The drive stands used in conjunction with the standard Erdco 100-mm roller bearing machines are of SwRI design and remain as outlined earlier[1].

3. Test Oil System

There have been no changes in the test oil system designed for this work[1]. The entire system has continued to give satisfactory performance.

4. Vent Trap

A vent trap was devised which permitted recovery of approximately 2/3 of the test oil escaping from the test oil sump as vapor or entrainment. Oil vapor and air passing out the sump vent were directed to a small ventilating blower having a 3-in. diameter rotor, operating at approximately 3030 rpm, with a capacity of 60 cfm. The blower was modified so that oil separated from the vapor and air escape path, by the action of the blower rotor, was retained in the blower housing from whence it was allowed to drain into a collector. Also taken into account in the modification was the necessity of keeping the recovered oil free of contamination. As a result, the motor was isolated from the blower housing, and the blower housing was modified such that it could be disassembled for thorough cleaning.

C. Test Procedures and Techniques

1. Operating Procedure

The operating procedure developed for this program was previously described[1]. No change in this procedure has been required in this work.

2. Deposit Demerit Rating Procedure

The deposit demerit rating procedure detailed previously[1] has remained the method by which deposit ratings were obtained. An overall

deposit demerit rating of less that 60 for the 48-hr test duration was considered acceptable by RTD for the purpose of the present program.

3. Test Oil Change

The test oil change schedule described previously[1] was followed for the tests reported herein. Oil degradation was considered satisfactory by RTD for this program if the initial oil change occurred after 16 hr of test and the total number of oil changes for the 48-hr test duration was 3 or less.

4. Test Termination

The criteria governing test termination discussed earlier[1] were followed throughout the work covered by this report.

5. Recovered Test Oil

During early testing with 5P4E, it was observed that large quantities of test oil were escaping through the sump vent, particularly at the higher temperatures and when air was introduced into the sump. Laboratory analysis of condensed test oil vapors revealed only slight changes in viscosity from that of the new or unused 5P4E. Because of this, it was felt that a suitable means should be devised whereby as much test oil vapor as possible could be trapped and returned to the test oil sump.

A vent trap, described previously, was devised which recovered approximately 2/3 of the test oil normally lost as vapor or entrainment. The test oil thus recovered was collected and returned to the test oil sump at 1-hr intervals throughout the 48-hr test period. The results of this action are discussed subsequently.

6. Viscosity Determination

Test oil viscosity determinations were made at 4-hr intervals in accordance with earlier work.[1]

For all testing of 5P4E polyphenyl ether, the reference temperature utilized in determining 100 percent viscosity increase was 210°F. The basis on which this temperature was selected has been discussed in detail earlier.[1] Briefly, because of the high pour point (+40°F) of 5P4E, and in order to avoid the possibility of non-Newtonian flow behavior of 5P4E at 100°F after experiencing degradation, RTD directed that 210°F be employed as the viscosity reference temperature. For similar reasons, this reference temperature was applied

to viscosity determinations of lubricant ATL-307. All other lubricants investigated during this program were subject to a viscosity reference temperature of 100°F. As a matter of record, both 100 and 210°F viscosity data were obtained for all candidate lubricants where possible.

7. Test Condition Selection

The selection of test conditions for this testing was intended to establish for all high-temperature candidate lubricants a reasonable temperature-deposit-deterioration profile by virtue of adequate investigation of each candidate. Of particular concern was the establishment, to the nearest 25°F increment, of the maximum test bearing and sump temperature combinations which would result in a deposit rating of approximately 60 and a viscosity increase of 100 percent in not less that 16 hours. These optimum performance conditions were to be established with no air to the sump; and after that, a follow-up test would be conducted to provide support information regarding the effect of air flow to the sump.

The complete accomplishment of the above objectives depended to a large extent upon the quantity of lubricant which was received for testing. In some instances, lubricants were available only in a limited quantity which prohibited the entire evaluation outlined above.

D. Test Results and Discussion

1. Test Results on 5P4E Polyphenyl Ether

In defining the high-temperature baseline performance of 5P4E lubricant F-1041, a total of 29 tests was conducted (6 tests were completed earlier and reported in Part I[1] of this report). Of the 29 tests, four tests at various temperature conditions did not complete the test schedule due to overheating of the roller bearing. Examination of the test bearings showed that excessive carbon and sludge formations had accumulated between the inner ring and cage. However, subsequent reruns of these tests resulted in satisfactory completion of the test schedule without the recurrence of excessive heat generation in the test bearing. Therefore, those tests in which the bearings overheated are considered as invalid and not included in the tabulation of results.

The following test conditions were initially selected to characterize the performance of 5P4E, without returning the condensed test oil to the test oil sump:

Oil Flow Rate, ml/min	600
Air Flow to Sump, cfm	0 and 1

Sump Temp, °F	Bearing Temp, °F
600	650
650	700
600	750
700	750

One test was conducted for each of these conditions, thus accounting for a total of 8 tests for this series. From this program, test temperatures were selected at which 12 additional evaluations were conducted to investigate the effects of returning condensed test oil to the test oil sump for recirculation. Three additional conditions were investigated at 650°F sump and 700°F test bearing temperatures. As a means of determining more completely the effect of air flow rate on test oil performance, 0.25 and 0.50 cfm air flow rates to the sump were utilized in two of the tests. The third test was carried out with a 1200 ml/min oil flow rate to the test bearing in an attempt to explore the effect of oil flow rate on deposits and degradation.

A total of 25 valid tests were performed on 5P4E polyphenyl ether (F-1041), in accordance with the above schedule. A summary of the test results is presented in Table 42. The individual summaries for Tests 10 through 15 have previously been reported[1]. The individual summaries for Tests 16 through 38* are given in Tables 64 through 82 in the Appendix. By grouping the test results according to sump and bearing temperatures as shown in Table 42, it is possible to compare the characteristic behavior of F-1041 at the various conditions. At a sump temperature of 600°F and a bearing temperature of 650°F, only a mild deterioration of the test oil was observed. Viscosity increases at these temperatures, following 48-hr testing, were approximately 10 percent, and, at these conditions, it appears that neither the addition of air to the sump nor the use of recovered test oil in the system exhibited any measurable effects on oil deterioration or deposit formation. There was a total absence of deposits in the test oil sump, and only small amounts of sludge collected on the filter elements. It should be pointed out that the filter element weight gains given in the individual test summaries are not due to deposit accumulation alone, since it was evident that test oil still remained on the elements after the specified drain period. This, in fact, was the case for all weights determined for filter elements used in the 5P4E evaluations.

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*Excluding Tests 19, 29, 33, and 37 which failed to complete the 48-hr test schedule.

TABLE 42. RESULTS OF 5P4E LUBRICANT DEPOSITS AND DEGRADATION

Air to Sump, cfm	Recovered Oil Returned	% Vis Increase at 210°F 16 hr	32 hr	48 hr	Oil Loss, ml/hr	Oil Change Time, hr	Overall Deposit Rating	Item Demerits Spacer and Nut	Heater Mount Front	Heater Mount Rear	Test Bearing	Rig No.	Test No.
					Temperature, Test Oil Sump/Test Bearing								
					600/650°F								
0	No	4.3	6.3	10.0	108	None	36	0	4	14	197	1	10
1	No	5.1	8.2	10.2	227	None	59	96	9	42	208	2	11
0	Yes	4.2	7.0	11.0	52	None	60	16	108	26	208	1	26
1	Yes	4.3	6.1	7.8	108	None	39	24	4	28	168	2	25
					500/700°F								
0	Yes	3.0	5.1	8.2	27	None	75	18	156	84	188	1	31
					600/700°F								
0	Yes	7.0	14.4	23.8	59	None	84	24	171	122	180	2	28
1	Yes	7.3	17.3	26.6	85	None	91	26	196	148	174	1	27
					650/700°F								
0	No	12.7	32.7	71.5	337	None	83	42	54	117	229	1	15
1	No	11.1	28.5	58.0	419	None	71	114	45	57	212	2	14
0	Yes	15.4	36.3	65.8	111	None	72	30	117	78	206	1	24
0	Yes	18.5	51.6	103(46 hr)	138	None	64	60	68	74	180	2	35
0	Yes	16.5	48.5	110(47.5 hr)	127	None	58	6	90	87	166	1	36
0	Yes	11.5	21.4	43.6	117	None	80	84	112	87	195	2	38
0(a)	Yes	21.0	65.9	103(41 hr)	92	None	57	30	52	54	196	2	30
0.25	Yes	18.1	55.9	111(44 hr)	132	None	51	12	78	52	156	1	34
0.50	Yes	34.4	62.7(b)	34.5	195	32(b)	87	72	108	122	223	2	32
1	Yes	13.5	35.7	96.6	171	None	76	102	64	86	205	2	21
					600/750°F								
0	No	9.1	16.3	25.2	135	None	124	108	194	236	206	2	17
1	No	4.8	9.2	12.7	198	None	123	96	225	146	260	1	16
0	Yes	8.3	15.5	28.3	104	None	143	102	262	273	222	2	18
1	Yes	9.4	14.0	18.7	123	None	139	90	348	160	231	1	22
					700/750°F								
0	No	52.8	60.8	104(41 hr)	533	28	96	70	57	189	255	2	13
1	No	71.0	24.1	162(44 hr)	862	24,36	112	99	110	207	250	1	12
0	Yes	78.9	2.5	99.0(44 hr)	196	16,31	96	30	166	147	225	2	23
1	Yes	34.8	151	120(47 hr)	333	36	107	90	190	130	226	1	20

Oil code F-1041
Test oil flow rate, ml/min 600
(a) 1200 ml/min test oil flow rate.
(b) Test oil changed at 32 hr due to error in laboratory determination of sample viscosity.

Of the three test oil sump temperatures investigated at the test bearing temperature of 700°F, emphasis was placed upon the 650°F test oil sump condition, as this appeared to be the most realistic test temperature differential. However, to obtain some idea of the 5P4E lubricant behavior at larger temperature differentials, two tests were run with a test oil sump temperature of 600°F, and a single test was carried out with the test oil sump at 500°F. At this latter test condition, the deterioration of F-1041 was extremely mild. The 600°F sump and 700°F bearing temperature conditions also gave a relatively low level of lubricant degradation with the viscosity increase being approximately 25 percent at the end of test.

With respect to the 650°F sump and 700°F bearing temperatures, there appears to be some accelerating influence of recovered test oil upon the deterioration rate of F-1041. Broadly speaking, there was an increase of approximately 40 percent in viscosity between tests for which recovered test oil was returned to the sump and those for which it was not. The presence or absence of air flow to the sump did not give any apparent or significant effect. It should be noted, however, that Test 24 gave viscosity values that did not fit into the behavior pattern, and subsequent running of the same conditions as Test 35 did result in values compatible with those from the other tests. Efforts to establish the reason or cause for this broad deviation between similar tests were unfruitful. Though Tests 24 and 35 were run on different bearing machines, it is not felt that the variation can be attributed to this fact, as the repeatability between the two machines has been previously shown to be good(1). The single test (Test 30) performed with a test oil flow of 1200 ml/min shows no significant difference in results from those tests performed with 600 ml/min.

In considering the overall deposit ratings, allowance must be made for the deficiencies inherent in the method of evaluation(1). With this in mind, the spread obtained for the 650°F sump and 700°F bearing temperature studies is not an unreasonable one. Because the minimum and maximum mean deviations are 19 and 17, respectively, and since there is no particular order to the deposit ratings obtained at the varied test conditions, it seems that the deposit characteristics of F-1041 are comparable at all conditions of air flow, oil flow, and recovered oil in the system covered by this work.

At the bearing temperature of 750°F, two sump temperatures, 600 and 700°F, were investigated. For the 600°F sump and 750°F bearing temperature tests, it was found that only moderate oil deterioration resulted, consistent with previous experience. However, deposits formed at these temperatures were the severest encountered with F-1041. The high test bearing temperature and extreme temperature differential (150°F) between the test oil and test bearing were evidently the responsible factors. Considerable

amounts of carbonaceous deposits were formed on the heater mount surfaces indicating that the test oil was coking severely on this hot surface. While the results at these temperature conditions seem to exhibit some dependency upon the other variables (such as air flow and the return of recovered oil), the differences are not marked enough, particularly for this type of study, to warrant confidence of such observations.

With respect to test oil degradation, test temperatures of 700°F sump and 750°F bearing brought about the most rapid breakdown of F-1041. These were the only F-1041 tests requiring test oil changes in completing the 48-hr test schedule. As is shown in Table 42, Tests 12 and 23 each required two changes of test oil in order to complete the test schedule, while Tests 13 and 20 required one oil change each. As might be expected, because of the extreme test temperatures, the test oil degradation rates appear to be somewhat less organized than those of other tests, but rapid deterioration trends can readily be seen. The overall deposit ratings were sufficiently consistent, within experimental limits, so as to indicate that all tests displayed essentially the same deposit behavior.

Generally speaking, the relationship between test bearing temperature and overall deposit formation is consistent. As shown in Figure 12, the overall deposit rating increases as the bearing temperature, and necessarily the overall test machine temperature, is increased. When considering viscosity increase, shown in Figure 13, there appears to be a direct dependency of oil deterioration upon increase in test oil sump (or bulk oil) temperature. There are no clear-cut effects discernible which seem to be attributable exclusively to the introduction of air to the test oil sump. However, from Table 42, it is apparent that the oil consumption rate is affected by the addition of air to the sump. This, obviously, was due to the increased air flow from the sump vent which removed the oil vapors and increased amounts of test oil by entrainment from the sump. The return of this recovered oil to the test oil system demonstrated no measurable influence upon the tests, though the recovered oil did possess a slight viscosity decrease from that of the fresh F-1041.

Table 42 shows that with F-1041 as the test lubricant, the largest contributing item to the overall deposit demerit rating was the test bearing. However, the general increase in test severity as indicated by the increase in overall deposit demerit ratings, at increasing test bearing temperatures, is not reflected to the same degree in the test bearing deposit demerit ratings, as shown in the following tabulation:

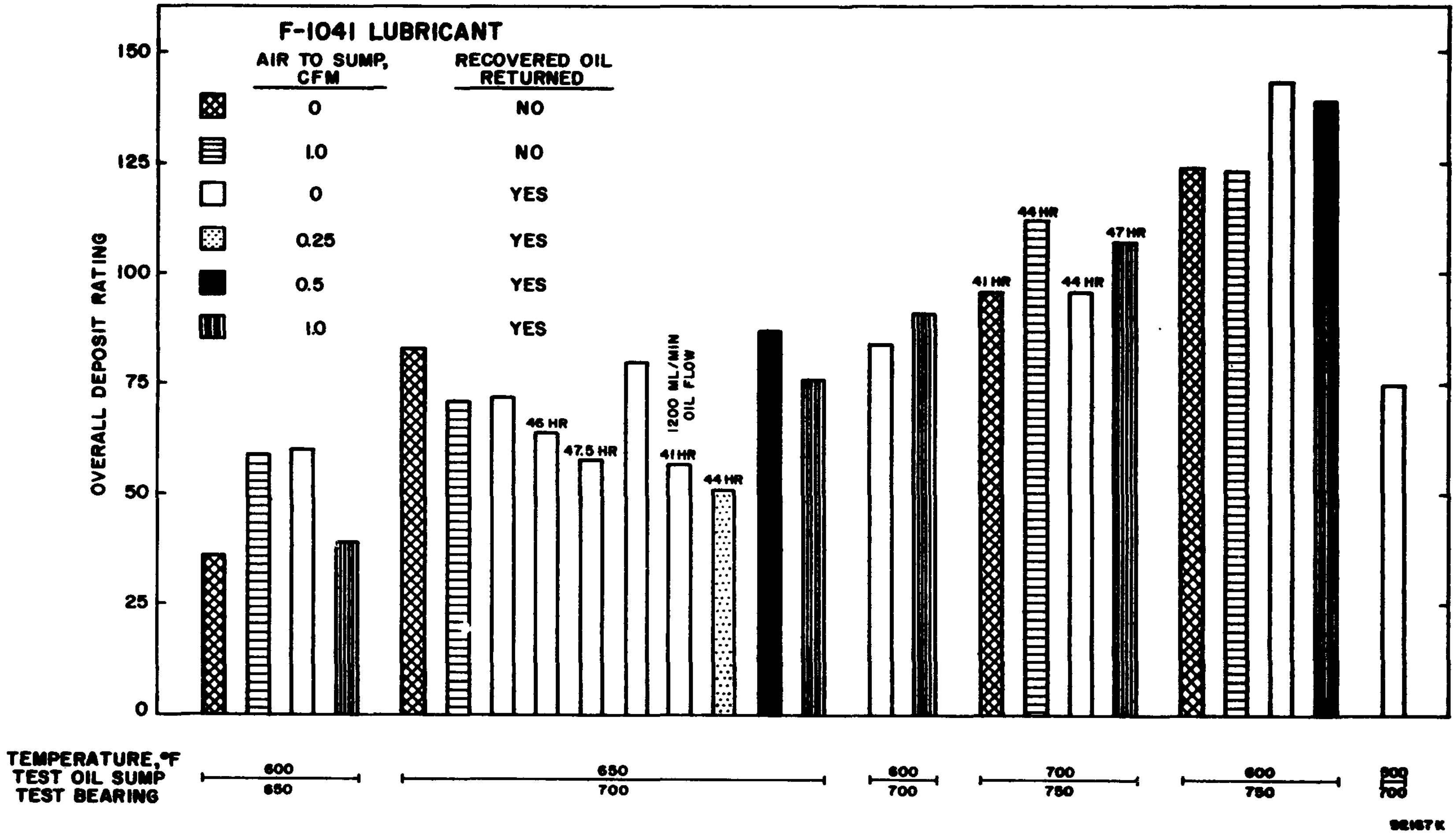

FIGURE 12. OVERALL DEPOSIT DEMERIT RATINGS OBTAINED FOR 5P4E UNDER VARIOUS TEST CONDITIONS

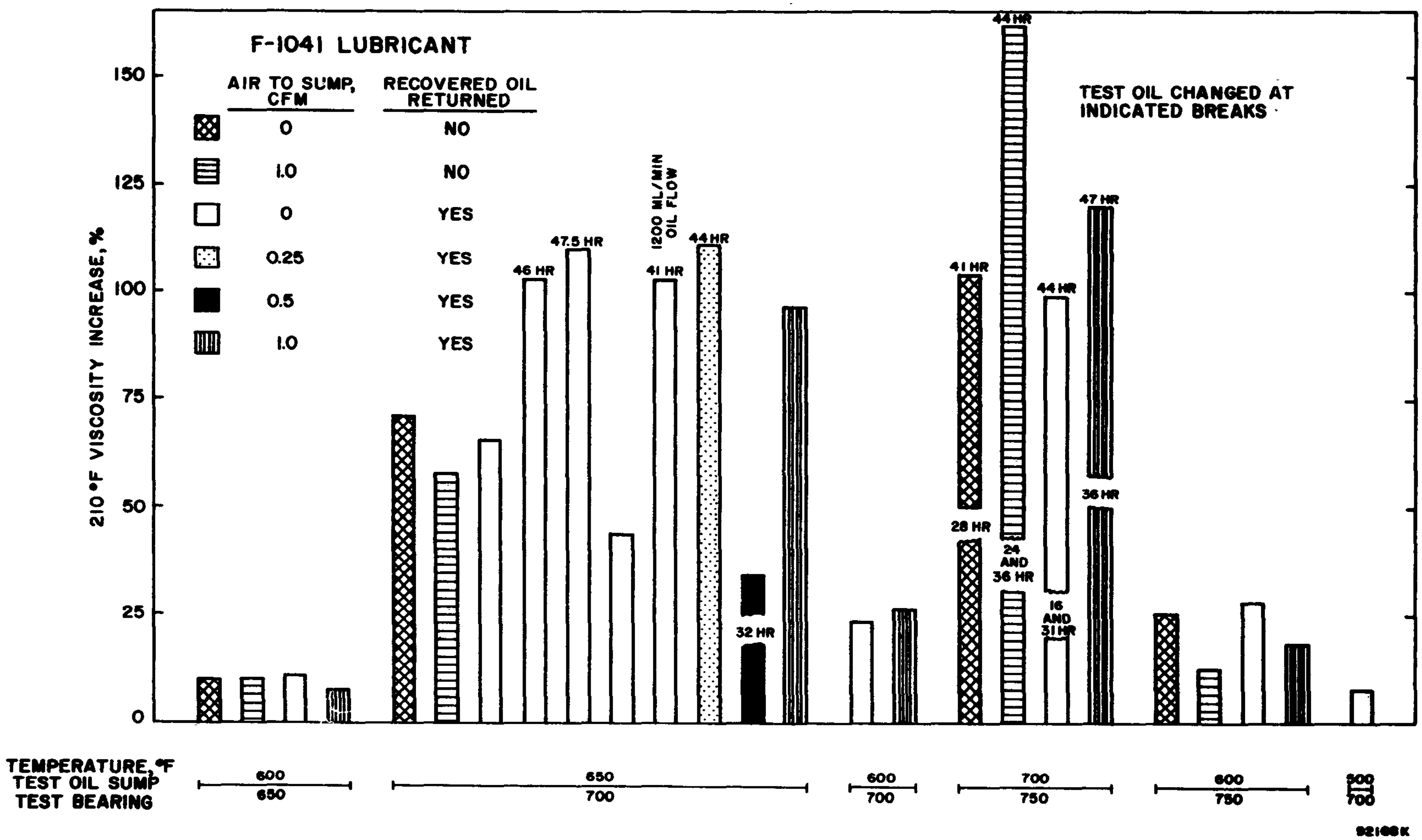

FIGURE 13. PERCENT VISCOSITY INCREASE FOR 5P4E UNDER VARIOUS TEST CONDITIONS

Test Bearing Temperature, °F	No. of Tests	Average Demerit Rating	
		Overall	Test Bearing
650	4	48.5	195.3
700	13	73.0	193.1
750	8	117.5	234.4

The average overall deposit demerit rating increased 52 and 142 percent when the test bearing temperature was increased from 650°F to 700 and 750°F, respectively. No significant change in the average demerit rating of the test bearing was noted when the temperature was increased from 650 to 700°F and only a 20 percent increase in the test bearing demerit rating was noted at the 750°F test condition. With respect to the test bearing rating, shown graphically in Figure 14, from 40 to 60 percent of the rating was due to the bearing cage. Quite consistently, the presence of light carbon was detected on the cage surfaces. Though a cursory inspection of the overall appearance of the bearings did not generally reflect such a high rating, the very light deposits of carbon, because of the weighted values assigned, contributed significantly to all of the bearing ratings.

In discussing the performance of F-1041, it should not go unmentioned that for the vast majority of tests, the sump remained remarkably clean. After draining and wiping away residual test oil, it was impossible to find deposits on the test oil sump. From the individual test summary sheets, it can be seen that when deposits were formed within the sump, they were of the varnish type and not at all extensive.

The metal specimens(1), which were placed in the test oil sump for all 5P4E tests, did not experience any significant weight changes at any of the operating temperatures or air flow conditions.

In order to strengthen the initial investigation into the repeatability of test machine performance(1), two repeat tests were conducted with F-1041 and these results compared with those obtained from two earlier tests. The previous tests (Tests 24 and 36), together with Tests 35 and 38, were performed two on each machine. All four tests were carried out under identical test conditions. The results of these tests, summarized in Table 43, serve to substantiate that the individual test machines were rating fluids with acceptable uniformity as to deposit forming tendencies. The small differences between deposit rating values obtained with each individual machine become even less significant when, again, one considers the method by which these values are determined. In this light, test repeatability is very reasonable since the maximum and minimum deviations from the overall deposit rating mean of the four tests are only 11.5 and 10.5, respectively.

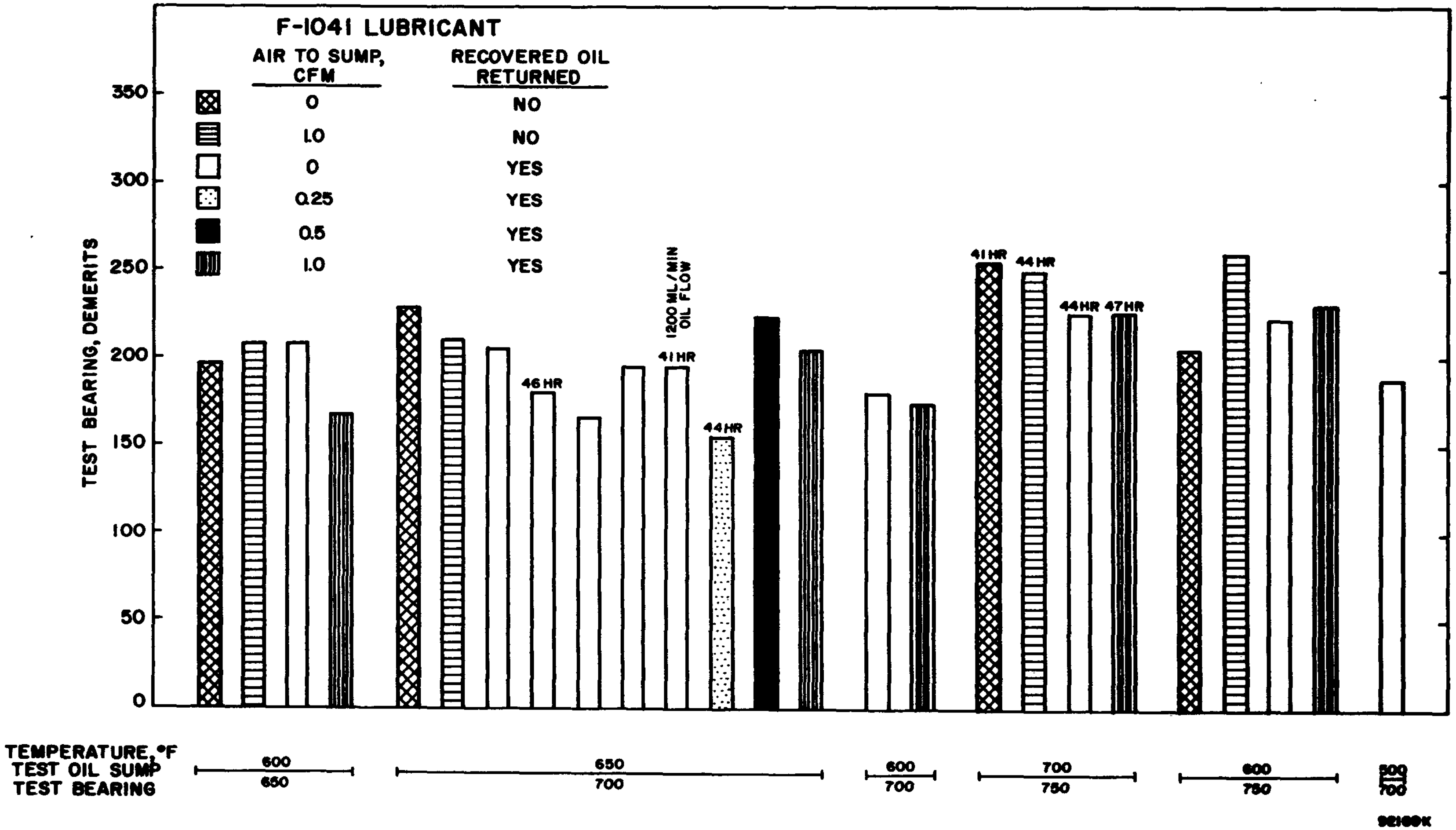

FIGURE 14. TEST BEARING DEPOSIT DEMERIT RATINGS FOR ALL 5P4E TESTS

TABLE 43. SUMMARY OF REPEATABILITY TEST RESULTS ON 5P4E POLYPHENYL ETHER

Test No.	24	36	35	38
Rig No.	1	1	2	2
% Vis increase, 210°F				
16 hr	15.4	16.5	18.5	11.5
32 hr	36.3	48.5	51.6	21.4
48 hr	65.8	110(a)	103(b)	43.6
Net oil loss, ml/hr	111	127	138	117
Overall deposit rating	72	58	64	80

Lubricant code	F-1041
Sump temp, °F	650
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

(a) 47-1/2 hr

(b) 46 hr

The rate of lubricant degradation appears less consistent than might be anticipated. Figure 15 shows the spread of 5P4E deterioration rates obtained for these tests. Past experience indicates that it is possible for a test fluid to undergo viscosity increases at different rates, under identical test conditions, though the trend remains in the same direction. This, obviously, is the phenomenon exhibited by F-1041 in these tests. It should be noted that the degradation rate extremes occurred once with each machine thereby excluding the possibility that one particular test machine promoted a more rapid degradation than the other.

2. Test Results on Candidate Lubricants

Eleven candidate lubricants were evaluated at various temperature conditions in the lubricant deposits and degradation phase of the program. A summary of the results obtained for the 11 lubricants is presented in Table 44. The detailed summaries for each individual test are presented (in the order that they appear in Table 44) in Tables 83 through 124 in the Appendix.

A discussion of the results obtained for each candidate lubricant is presented in the following section of this report.

a. Test Results on O-62-25

At the request of RTD, investigation of O-62-25, a MIL-L-9236 lubricant, was undertaken to obtain performance data for this fluid. The initial test temperatures selected were 425°F sump and 500°F test bearing. The reference temperature used for determining viscosity increase of O-62-25 was 100°F.

Test 45 (Table 87) performed at the above mentioned test temperatures, resulted in a demerit rating of 120.6 while the test oil viscosity underwent an increase of approximately 70 percent following 48 hours of testing. Because of the excessive deposit rating, it was considered necessary that the test bearing temperature be lowered in subsequent testing. Also, the maximum sump temperature at which satisfactory oil deterioration could be obtained seemed to be in excess of 425°F. Consequently, the test temperatures of 450°F sump and 475°F test bearing were selected for the ensuing test.

The overall deposit rating determined for this test (Test 46, Table 88) was 35.2. It will be noted that the severity of deposit formation on the heater mount, as well as the test bearing, was greatly reduced. The degradation behavior of O-62-25 was not significantly affected by the increase in sump temperature. Thus, by virtue of Tests 45 and 46, the maximum temperatures at which O-62-25 might perform satisfactorily were established.

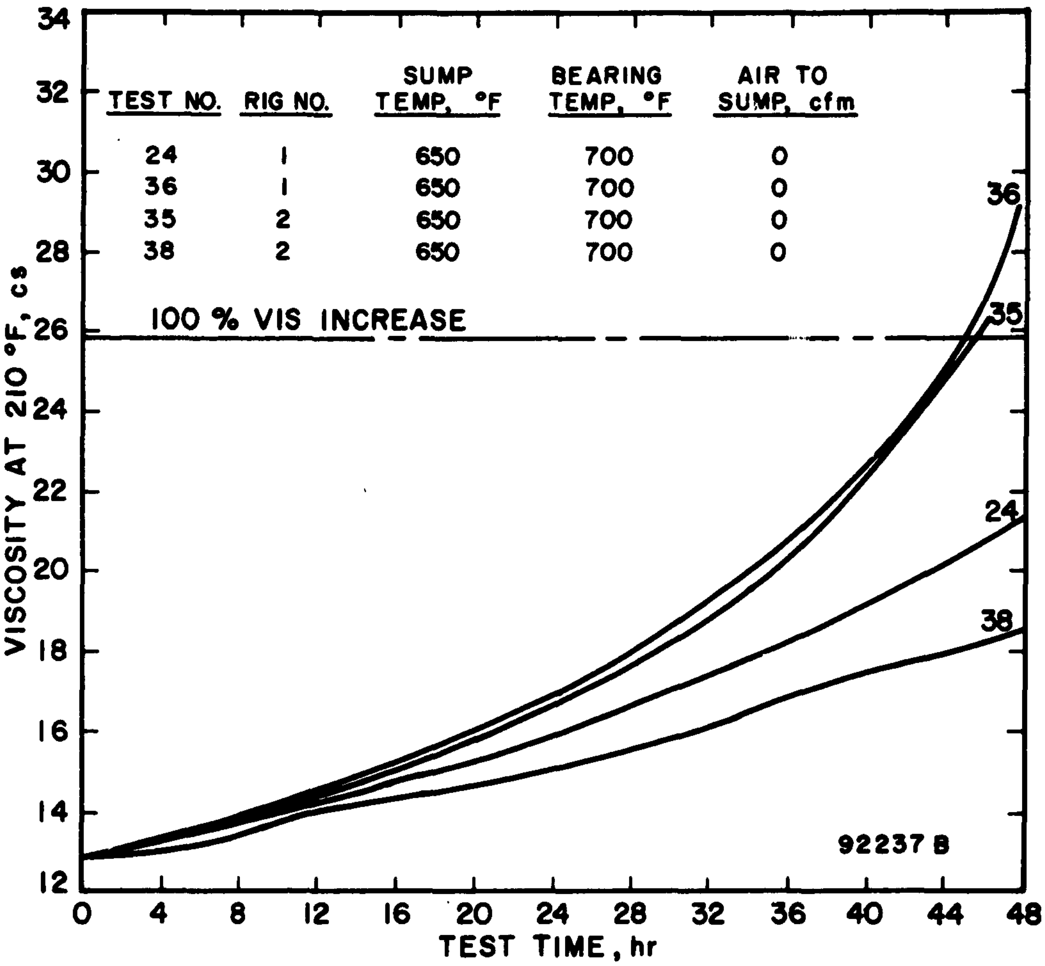

FIGURE 15. VISCOSITY INCREASE OF 5P4E POLYPHENYL ETHER OBTAINED IN 100-MM BEARING TEST

TABLE 44. SUMMARY OF LUBRICANT DEPOSITS AND DEGRADATION RESULTS ON ELEVEN CANDIDATE LUBRICANTS

Oil Code	Test Temp, °F Sump	Test Temp, °F Bearing	Overall Deposit Rating	Times to Test Oil Changes, hr	Viscosity Increase at End of Test, %(a)	Oil Loss, ml/hr	Test No.	Rig No.
O-62-25	425	475	50		27	67	47	2
	425	475	68		33	74	48	2
	425	475	37		33	85	49	1
	425	475	33		29	76	50	1
	425	500	121		70	93	45	2
	450	475	35		73	130	46	2
H-1001	425	575(b)	104		76	96	76	1
	425	575	79		42	55	66	1
	425	575	91		64	50	72	1
	450	500	36		70	53	51	2
	475	525	32	32	48	116	52	2
	500	550	39	24, 44	104	121	53	2
	525	575	51	21.5, 40	48	148	54	2
	525	575	62	16, 28, 43	104	207	59	2
	525	575	80	16, 32	89	213	60	1
	525	575(c)	47	21, 39	56	202	61	1
	525	575	59	19.5, 38.5	56	197	62	1
	525	575	58	19.5, 37	63	210	63	1
	525	575	66	14, 26.5, 39.5	70	227	64	2
	525	575(b)	67	10, 16, 22.5, 27.5, 33.5, 39, 43.8	99	323	65	2
	550	600	102	12, 23, 32, 42.5	91.5	254	55	2
O-64-13	425	575(d)	119		84	114	77	2
	425	575(e)	154		101	111	79	2
	525	575	135	15.5, 29, 43.5	113	312	80	1
O-64-17	425	525	115		66	62	88	2
ATL-304	500	550	57	16, 32	122	117	39	1
ATL-305	475	575	69	21, 40	49	138	44	1
	475	625	126	23.3	104	118	43	1
	500	550	18	12, 27, 40	65	161	42	1
ATL-307	500	588(f)	112		6.3	15	41	2
	650	700(g)	580		11.6	148	40	2
ATL-401	425	575	57		99	79	70	2
	425	575(h)	63		100	73	58	1
	425	575(b)	68	28	71	116	78	2
	475	575	44	27	90.3	120	56	1
	500	575	45	20, 39.5	50	196	73	1
	525	575	57	11, 24, 36, 47	109	283	71	2
ATL-402	500	550	39	27.5	84	132	67	1
	525	575	104	20.5, 39	34	172	68	1
ATL-403	500	550	116	16, 32	56	209	69	2
ATL-405	425	500	88		70	58	75	2
	425	575	167	46.3	100	76	74	2

(a)The viscosity increase presented for all lubricants except ATL-307 is based upon 100°F data. Viscosity increase for ATL-307 is based upon 210°F data.

(b)Test conducted with 1 cfm air to sump.

(c)Test bearing temperature was 560°F during first 16 hr of operation.

(d)Test was terminated at 32 hr due to excessive deposit formation.

(e)Test oil loss of approximately 3000 ml was made up at 13.3-hr testing.

(f)Test bearing temperature average with no heat from test bearing heater.

(g)Test terminated at 11.6 hr due to excessive deposit formation.

(h)Cu and Mg specimens added to the 5-metal specimen set.

However, in order to obtain information which is more representative of actual application, test temperatures of 475°F test bearing and 425°F sump were selected for additional testing, thus allowing a more realistic temperature differential between the test bearing and bulk test oil. The results from this test (Test 47, Table 83) indicate that at these temperatures, O-62-25 gives very satisfactory performance. The deposits, which resulted in an overall deposit rating of 49.8, were chiefly of the varnish and sludge varieties. The appearance of the test bearing was good and showed no excessive deposit accumulation. At the completion of this test, O-62-25 had undergone a viscosity increase of about 27 percent indicating excellent stability at this temperature environment.

As a check on the precision of the results, two additional tests (Tests 48 and 49, Tables 84 and 85) were conducted, one on each of the two bearing machines used for this study. The results from these tests also supported the satisfactory performance of O-62-25 at test temperatures of 425°F sump and 475°F test bearing. In particular, the data were in excellent agreement with respect to lubricant degradation. When considering the deposit ratings for these tests, however, the values obtained did not quite give the agreement that was expected. Test 48 was found to have a rating of 68.1, and Test 49 resulted in a rating of 36.6. Closer examination of the rated areas for these three tests showed that the most significant variations existed with the heater mount surfaces. Insofar as the deposits accumulated on these surfaces were of the same types, the variation was one of a quantitative rather than a qualitative nature.

The significant spread of deposit demerit ratings from the two bearing rigs was disconcerting, in view of the excellent rig reproducibility obtained earlier.(1) The only observed difference between the three tests in question was the pressure required to maintain the prescribed test oil flow. Both tests conducted with test machine No. 2 required from 11 to 11.5 psi to maintain the proper flow while the test with test machine No. 1 required a pressure of 18 to 18.5 psi to provide the desired test oil flow.

Thus, an additional test, at the same test temperatures and utilizing bearing machine No. 1, was needed for a more realistic comparison of the machines. Prior to this, however, the logical approach was to ensure that both test machines were operating identically within experimental limits. Toward this end, an exhaustive search failed to reveal any significant variable existing between the two test machines other then the pressure required to maintain test oil flow. This difference occurred even though the jet orifice of each bearing machine was found to meet specification. In view of this, the jet assemblies were interchanged thereby permitting bearing machine No. 1 to operate at the lower test oil pressure. The presumption, of course, was that should the test

oil pressure be influencing the accumulation of deposits within the machine, those effects would be demonstrated on the subsequent test. The results of such a test (Test 50, Table 86) failed to indicate that test oil pressure was in any way responsible for the spread of the ratings. This test resulted in an overall rating of 33.2 which compared very favorably with the rating of 36.6 obtained from the first test (Test 49) conducted with machine No. 1.

In light of these results obtained with O-62-25, which are summarized in Table 45, it appeared that bearing machine No. 2 was now rating somewhat more severely than machine No. 1. However inasmuch as previous work[1] has indicated very satisfactory test reproducibility with two other lubricants; and, insofar as investigation into the existence of some significant operating difference between test installations proved unsuccessful, one should not overlook the possibility that this degree of repeatability might be peculiar to the lubricant being employed rather than a consequence of the test machines. Because of this, it was felt that another lubricant should be selected in confirming the level of test reproducibility between machines. Additional repeat evaluations with O-62-25 were precluded by the depletion of the supply of this lubricant. Further investigations on test reproducibility are discussed in the subsequent section for lubricant H-1001.

b. Test Results on H-1001

Investigation of lubricant H-1001 was conducted to establish the performance capability for this fluid. Testing was initiated at a sump temperature of 450°F and a test bearing temperature of 500°F (Test 51, Table 92). At these temperatures, H-1001 gave very satisfactory performance. Test oil consumption was low, and the initial test oil charge showed a viscosity increase of approximately 70 percent at the completion of the test. The test bearing from this test was found to be very clean in appearance, and no excessive deposit accumulation occurred within the test machine. Especially impressive was the almost total absence of the severer, carbon-type deposits. These observations are reflected by the overall rating of 35.5 for Test 51.

Maintaining a 50°F differential between the sump and test bearing temperature, the test temperatures for H-1001 were increased in 25°F increments. Consequently, the succeeding test was performed at temperatures of 475°F sump and 525°F test bearing. This test (not included in Table 44) resulted in a catastrophic failure of the test bearing following 2.5 hr of testing. Examination of the bearing fragments showed evidence that failure of the bearing was a consequence of severe cage wear that reached a point which allowed the retainer rivets and rollers to become free. The degree of deposit formation at this time was nil and could not have been a contriburing factor to the failure. Also,

TABLE 45. COMPARISON OF BEARING TEST RESULTS ON LUBRICANT O-62-25

Test No.	47	48	49	50
Rig No.	2	2	1	1
% Vis increase, 100°F				
16 hr	10.5	10.4	10.2	9.5
32 hr	17.4	17.9	19.8	17.1
48 hr	27.0	33.0	33.1	29.0
Net oil loss, ml/hr	67	74	85	76
Overall deposit rating	49.8	68.1	36.6	33.2
Item demerit rating				
End cover	3	3	3	3
Spacer and nut	18	60	20	24
Heater mount, F	132	138	39	76.5
Heater mount, R	51	105	61.5	30
Seal plate	3	10	0	3
Test bearing	92	92.5	96	62.5

Sump temp, °F 425
Bearing temp, °F 475
Air flow to bearing machine, cfm, 0.35

inspection of the bearing, prior to its use, did not indicate any manufacturing defects.

A second test (Test 52, Table 93) at these temperatures was attempted and successfully completed. An overall deposit rating of 32.1 was recorded at a sump temperature of 475°F and a test bearing temperature of 525°F. Though the overall deposit rating showed no increase with an increase in bearing temperature, it was quite evident that the evaluation of sump temperature resulted in a significant influence upon the degradation and consumption rates of H-1001. During this test, it was necessary to renew the test oil charge following 32 hr of testing as a consequence of 100 percent viscosity increase. Also, test oil consumption was, at 116 ml/hr, approximately twice that of the previous test condition.

Lubricant H-1001 was also investigated at temperatures of 500°F sump and 550°F test bearing (Test 53, Table 94). This test resulted in a very satisfactory overall rating of 38.8. Again, an increase in test bearing temperature did not bring about a significant increase in deposit formation. Quite apparent, through, was the marked effect the increase in sump temperature had upon the test oil. Because of viscosity increase, the test oil had to be renewed after 23.5 hr of testing and the test was terminated at 44 hr. The data gathered from Test 53 indicate that lubricant H-1001 can perform satisfactorily at these temperatures, if up to 3 oil changes are allowed.

The performance capability of H-1001 was next investigated at test temperatures of 525°F sump and 575°F test bearing. It was noticed after 2.5 hr of testing that metal particles were in the test oil stream. The test (not included in Table 44) was interrupted so that a visual check of the test machine interior could be made. It was found that considerable cage wear had taken place and cage breakage was imminent. Therefore, the test was discontinued. A second effort to carry out a test at these temperatures was made and successfully completed (Test 54, Table 95). This test resulted in an overall deposit rating of 51.3, and the degradation rate continued to show the adverse effects of sump temperature elevation. Twice, following 21.5 and 40 hr of test time, it was necessary to recharge the test oil sump in order to complete the 48-hr test schedule. At these temperatures, test oil consumption was 148 ml/hr. From these data one would conclude that satisfactory performance of H-1001 at a sump temperature of 525°F and a bearing temperature of 575°F can be expected, if up to 3 oil changes are allowed.

Because the increases in deposits and consumption rate were so gradual, it was felt that the capability of H-1001 should be determined at a sump temperature of 550°F and a test bearing temperature of 600°F

(Test 55, Table 103). As anticipated, the rate of degradation was quite rapid at these temperatures and, because of attaining 100 percent viscosity increase, the test oil had to be replaced at 12, 23, and 32 hr of testing, and the test was terminated at 42.5 hr. Somewhat surprising, however, was the abrupt increase in deposits and oil consumption demonstrated by H-1001 at these temperatures. The test bearing temperature of 600°F yielded an overall rating of 102.2, a value approximately twice that obtained with a 575°F bearing temperature. Also, the increase in sump temperature to 550°F almost doubled the rate of oil consumption. Thus, the temperatures employed in this test resulted in an unacceptable performance of H-1001, both from a deposit as well as a deterioration standpoint.

Having reached the maximum temperature limits of performance for H-1001, it was felt desirable to conduct a series of repeat tests with this lubricant at the temperatures of 525 and 575°F. This series of tests would serve a twofold purpose. First, the precision of the performance limit would be established. Secondly, the level of test machine repeatability, using another lubricant, would be demonstrated. The first repeat test of this series (not included in Table 44) was aborted because small particles of metal began appearing in the test oil as the test was being shut down to perform the 16-hr interim inspection. The test machine was inspected, and it was discovered that cage wear had taken place to a degree which prohibited test continuation.

A subsequent test (Test 59, Table 96) was successfully completed at these temperatures, and the deposit rating for this test was 61.8. This value compared quite favorably with the rating of 51.3 obtained for Test 54, also on machine No. 2 under identical test temperatures. However, the rate of lubricant degradation for Test 59 increased significantly over that of the earlier evaluation, and test oil changes were required at 16 and 28 hr of testing with the test requiring termination at 43 hr as a result of viscosity increase.

Continuing investigation of lubricant H-1001 performance at temperatures of 525°F sump and 575°F test bearing resulted in the completion of five additional tests at this temperature environment. Of these, Test 61 (Table 98) cannot be considered valid. Upon initiation of this test, it developed that the prescribed test bearing temperature could not be attained. Inasmuch as efforts to correct this discrepancy were unsuccessful until the test had completed 16 hr operation, the test bearing temperature during this time was 560°F rather than the specified 575°F. This temperature deviation appears to be reflected in the low overall deposit rating determined for this test.

The remaining tests, Tests 60, 62, 63, and 64 (Tables 97, 99, 100, and 101) were conducted such that, combined with Tests 54 and 59, a total of three evaluations were made on each of the two bearing machines

being utilized in this program. A comparison of these test results is presented in Table 46. It will be noted that the overall agreement of data is very good. These data indicate, as previously noted[1] with O-61-17 and F-1041, that a very satisfactory level of reproducibility exists between test installations. Further, the five latter tests were carried out free of incident.

The frequency of test loss due to excessive cage wear in the early testing of H-1001 had caused considerable concern. Though evidence of cage wear occurring on the I. D. of the test bearing was observed in all these tests except one, the amount of wear was generally only perceptible to slight and never approached a degree of significance. Measurements made on these bearings suggested that test bearing clearance tolerances might well be responsible for the wear observed. It should be mentioned that this type of wear was later experienced in tests with lubricants other than H-1001 and at various temperatures.

In order to gain some knowledge of H-1001 behavior when exposed to relatively high air flow, Test 65 (Table 102) was performed at 525°F sump and 575°F bearing temperatures with the introduction of 1 cfm water-saturated air to the test oil sump during the test. It will be noted that the 1 cfm air flow to the sump had a pronounced adverse effect upon the deterioration rate of the lubricant. Though deposit formation was not noticeably affected, the rate of degradation became so rapid that, as a consequence of viscosity increase, this evaluation required six test oil changes and necessitated termination of the test following approximately 44 hr of testing. On the strength of one test, there seems to be little doubt that water-saturated air flow to the sump results in a most undesirable influence on lubricant H-1001. The introduction of air to the test oil sump also resulted in an increase of approximately 60 percent in test oil consumption rate over those tests conducted at 525°F sump temperature where air was not added to the sump. The deposits, however, were consistent, both qualitatively and quantitatively with those observed for other H-1001 investigations at these temperature conditions.

The effects of a large temperature differential, between sump and test bearing, on H-1001 were also explored. Two tests (Tests 66 and 72, Tables 90 and 91) were performed maintaining a bearing temperature of 575°F while lowering the sump temperature to 425°F. This lowering of sump temperature showed a corresponding drop in test oil degradation and consumption rates while the temperature differential of 150°F appeared to increase the overall level of deposit formation. In particular, the heater mount front surface for both these tests showed significant gains in deposits over those generally recorded for H-1001 at a 575°F test bearing temperature.

TABLE 46. COMPARISON OF BEARING TEST RESULTS ON LUBRICANT H-1001

Test No.	54	59	64	60	62	63
Rig No.	2	2	2	1	1	1
Item demerit rating						
End cover	0	0	0	0	0	0
Spacer & nut	20	33	34	72	24	30
Heater, F	99	126	79.5	126	61.5	75
Heater, R	96	102	160.5	120	186	139.5
Seal plate	0	0	0	0	0	0
Test bearing	92.5	110	122.5	160	84	104
Overall rating	51.3	61.8	66.1	79.7	59.3	58.1
Oil loss, ml/hr	148	207	227	213	197	210
Test oil change time, hr	21.5 40	16 28(a)	14 26.5 39.5	16 32	19.5 38.5	19.5 37

Sump temp, °F 525
Bearing temp, °F 575
Air flow to bearing machine, cfm 0.35
Air flow to test oil sump, cfm 0

(a) Test terminated at 43 hr due to viscosity increase.

Having carried out these evaluations, it was felt that the test conditions should be repeated with the introduction of 1 cfm water-saturated air to the test oil sump to determine what effect this action might have on the test results. This test (Test 76, Table 89) resulted in an overall deposit rating of 103.5. The values obtained for the previously performed tests without air to the sump were 78.8 and 91.3, averaging approximately 85. Thus it would appear that a slight increase in deposit formation might occur with this temperature condition as a consequence of air flow to the sump. The degradation rate did not exhibit any pronounced change as a result of the addition of air to the sump at 425°F. As would be expected, the test oil consumption increased significantly by approximately 80 percent. Generally speaking, however, no marked difference was observed between these tests, with or without air to the sump.

Several observations of a general nature can be made from the H-1001 tests. These tests indicate that the test bearing in particular and the bearing machine in general experience no significant difference in deposit formation with H-1001 at the different test bearing temperatures of 500, 525, and 550°F. Quite obviously, the rate of oil degradation increases with an increase in sump temperature; however, for each individual test the rate of deterioration was almost constant. Contrary to results with F-1041[1] following a test oil renewal, residual test oil in the system had little or no adverse effect upon the degradation behavior of the fresh charge. Excluding the test conducted at 550 and 600°F, the absence of significant formation of sludge and carbon was quite noticeable. The chief deposit formed with H-1001 was varnish, and the filter weights did not indicate any noteworthy amounts of suspended deposits in the test oil. At none of the test conditions was it possible to detect any corrosive action of H-1001 upon the metal specimens.

Of the tests attempted with lubricant H-1001, three could not be completed because of test bearing cage wear. This occurrence of test loss was particularly disturbing since the wear was not precipitated by detrimental deposit formation. All previous test bearing failures (a total of three out of 50 tests) were traced to severe deposit formation which accumulated between the bearing cage and inner race. Also, these failures transpired at extreme bearing temperatures of 700 and 750°F. Efforts to establish unequivocally the cause of cage wear experienced in the H-1001 tests were unsuccessful.

c. Test Results on O-64-13

Initial evaluation of lubricant O-64-13 was begun at a sump and test bearing temperature of 425 and 525°F, respectively. This test (Test 77, Table 104) resulted in premature termination after 32 hr testing as a consequence of excessive deposit formation. At this time, the lubricant had undergone a viscosity increase of approximately 84 percent, and oil consumption

was 114 ml/hr over this period of operation. The overall rating determined for O-64-13 after 32-hr testing was 118.8, indicating that a test bearing temperature of 525°F might be beyond the capability of O-64-13. Nevertheless, on request of RTD, these test conditions were repeated with O-64-13, and the test (Test 79, Table 105) was permitted to complete the test schedule. These data clearly follow the trend established by Test 77, and it appears that if Test 77 had been continued to 48 hr, the results would have been in very close agreement with those obtained for Test 79. Because of an unavoidable test oil loss of approximately 3000 ml at 13.3 hr, it is probable that the lubricant degradation results of Test 79 are somewhat less severe than would be expected. However, deposit formation at the 425°F sump and 575°F test bearing condition was unquestionably high.

In an attempt to obtain a more favorable overall deposit rating for lubricant O-64-13 at 575°F test bearing temperature, an additional test was carried out at this bearing temperature with an elevated sump temperature of 525°F. Results from this test (Test 80, Table 106) indicate that these temperatures are likewise beyond the capability of O-64-13. The general appearance of the bearing machine at the termination of this test was unsatisfactory with all rated areas extensively covered with deposits. In particular, the test bearing was heavily coated with deposits of the carbon class. Two test lubricant changes were required in the course of the test, and termination of the test was necessary after 43.5-hr testing because of viscosity increase. In addition, consumption rate was a considerable 312 ml/hr. In all O-64-13 testing, examination of the metal specimens did not show signs of corrosive attack by the lubricant.

d. Test Results on O-64-17

A single evaluation of lubricant O-64-17 was conducted during this program. The test temperatures selected were 425°F sump and 525°F bearing (Test 88, Table 107). Results of this test show O-64-17 to be very adversely affected by these temperatures with respect to deposit formation. Extensive sludge and carbon accumulation accounted for the major portion of the overall rating of 114.9. At the completion of the test, the initial lubricant charge had undergone a viscosity increase of 66 percent, and the rate of oil consumption was established at 62 ml/hr. Upon examination, the metal specimens did not indicate corrosive attack by lubricant O-64-17.

e. Test Results on ATL-304

Candidate lubricant ATL-304 was investigated at temperatures of 500°F sump and 550°F test bearing (Test 39, Table 108). At these test conditions, ATL-304 gave satisfactory results with respect to deposit formation

as reflected by an overall deposit rating of 57.1. It was necessary, however, to drain and recharge the test oil system twice during the test due to fluid viscosity increase of 100 percent. The rate of viscosity increase for ATL-304, at these temperatures, was approximately 100 percent every 16 hr per test oil charge. The reference temperature used for determining 100 percent viscosity increase for ATL-304 was 100°F as directed by RTD. No significant weight changes were noted for the metal specimens at the sump temperature of 500°F.

f. Test Results on ATL-305

Candidate lubricant ATL-305 performance was first investigated at a sump temperature of 500°F and a test bearing temperature of 550°F (Test 42, Table 111). ATL-305 displayed an unusually low tendency toward deposit formation at these temperature conditions. After completing 48 hr of testing, there was very little difference in the deposits accumulated at this time and the small amount observed at the 16-hr interim inspection. The rated areas of the bearing machine were remarkable free of deposits and, in particular, those items which generally contribute the major portion of the deposit rating were unusually clean. Those deposits which were formed consisted chiefly of varnish and sludge. The excellent deposition behavior of ATL-305 at these temperature conditions is evidenced by the very low overall deposit rating of 18.2.

From the test oil degradation standpoint, this lubricant was less satisfactory. In the course of completing the 48-hr test schedule, it was necessary to recharge the test oil sump after 12, 27, and 40 hr of testing. At each of these times, the test oil viscosity reached an increase of 100 percent based on a reference temperature of 100°F. Thus, a total of eight gallons of test fluid, plus an average consumption of 161 ml/hr between lubricant changes, was required to complete Test 42. The test metal specimens did not yield significant weight changes at the sump temperature of 500°F.

At the request of RTD, lubricant ATL-305 was then evaluated at a sump temperature of 475°F and a test bearing temperature of 625°F (Test 43, Table 110). As anticipated, only a single change of test oil was required as a consequence of the test oil attaining a 100 percent viscosity increase during the course of the test. This test was terminated after 47 hours of testing, at which time the test oil once more attained a 100-percent viscosity increase.

The overall deposit rating for this test was 125.7, a value well beyond that considered acceptable. The major deposit formations occurred on the heater mount front and rear with considerable amounts of

carbon of the crinkled, blistered, and flaked types accumulating on these areas. The test bearing deposits were not extreme, though the bearing outer race had accumulated a light smooth carbon coating over approximately 45 percent of its front and rear surface. The metal specimens placed within the test oil sump during testing gave no suggestion of being affected by ATL-305.

With these results in mind, it was decided to reduce the test bearing temperature while maintaining the sump temperature at 475°F (Test 44, Table 109). This test showed that at test temperatures of 475°F sump and 575°F bearing, a significant reduction in deposit formation was effected. Only very small amounts of the severer carbon deposits were formed as evidenced by the overall deposit rating of 69.3. With respect to distribution, the largest accumulation of deposits again occurred on the heater mount front and rear. Following the criteria for renewal of test oil charge, it was necessary to change test oil twice during the completion of this test. Nonetheless, it is readily seen in Figure 16 that the degradation behavior of ATL-305 was quite similar for both tests conducted at 475°F sump temperature and certainly not unusual for testing of this nature.

The test bearing from Test 44 was quite clean in appearance giving indication of only slight deposit buildup. The metal specimens included in these tests gave evidence of no significant weight change.

g. Test Results on ATL-307

The performance of candidate lubricant ATL-307 was investigated under two sets of operating temperatures. Test 40 (Table 113) was conducted at a sump temperature of 650°F and a test bearing temperature of 700°F. The test bearing, when operating with ATL-307, had an unusually high stabilization temperature of 490°F. This stabilization temperature was approximately 125°F greater than any encountered during all testing with other lubricant types. The customary maximum bearing stabilization temperature of 375°F was waived, and the test was allowed to proceed. The test was interrupted at 7.5 and again at 11.7 hr of test time as a result of test oil pressure pump failure. These failures were the consequence of hard deposits accumulating between the pump shafts and their bearing surfaces. At the latter time, all items located within the test oil sump were completely coated with a reddish brown substance quite similar in appearance to ferric oxide. The test oil sump wall and bottom were completely covered with a heavy deposit of dark brown material that appeared to be flaking away from the sump. Because the general appearance of the test oil system indicated heavy deposit formation, the end cover of the bearing machine was removed and the machine was inspected.

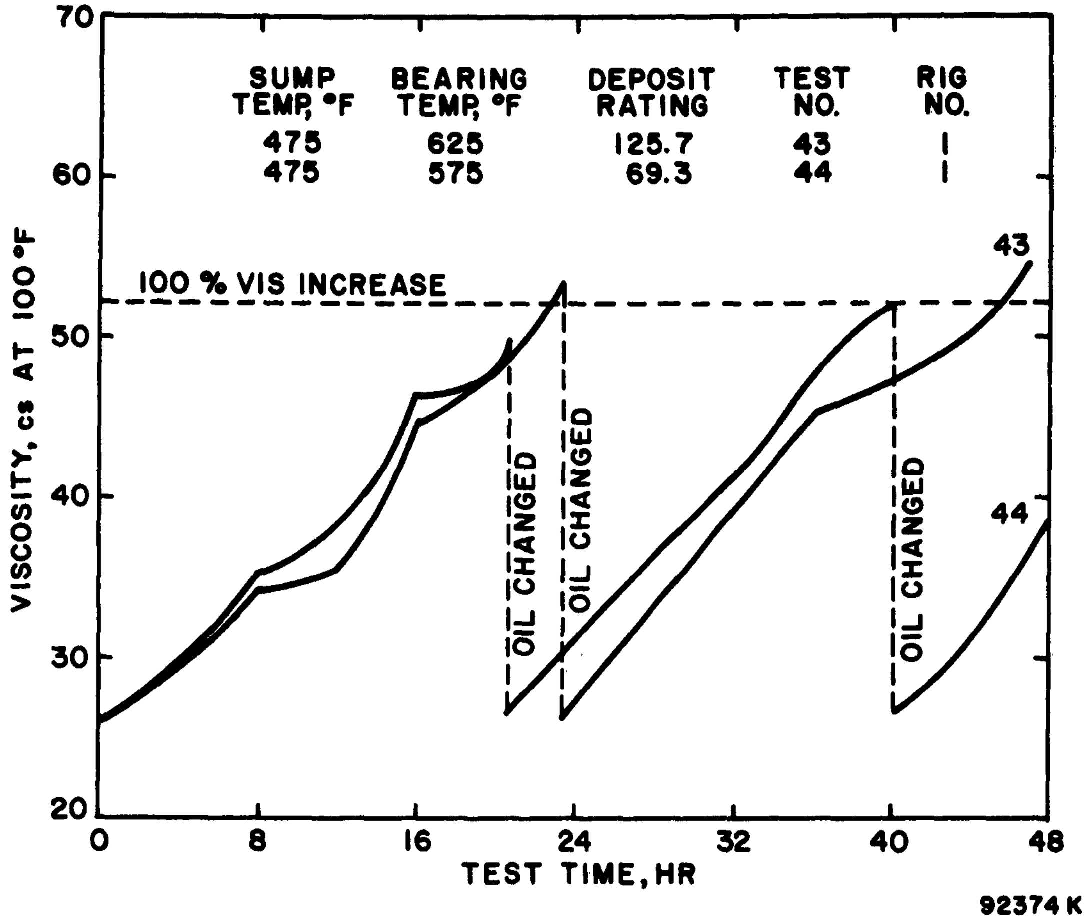

FIGURE 16. VISCOSITY INCREASE OF ATL-305 OBTAINED IN 100-MM BEARING TEST

This inspection revealed deposits not like any obtained with other lubricant types. In order to arrive at some idea of the relative amount of deposit formation, a deposit demerit rating was obtained. To do so, it was necessary to ignore the color of the various deposits and, relying upon consistency and thickness alone, these deposits were defined in terms of the common types of deposit formations. The largest portion of the deposits fell into the "sludge" or "carbon" class with a considerable amount of flaked carbon prevalent; and only a small amount of deposits, present on the test bearing rollers, appeared to fall into the varnish class. The deposits rated as sludge ranged from greyish white to dark grey and brown in color, while those classed as carbon were light reddish brown to dark brown in color. Deposit formation was so severe that, following 11.7 hr of test time, the overall deposit rating was 580. Thus at this time, the test was terminated.

As in the oxidation-corrosion test, ATL-307 gave evidence of affecting the metal specimens mounted within the sump. In particular, titanium and stainless steel displayed significant weight losses. The changes in weight resulting from sample exposure to the lubricant at 650°F (Test 40) are listed as follows:

Metal Specimen	Weight Change, mg/cm^2
Aluminum	+0.22
Titanium	-1.44
Silver	-0.02
Steel	+2.74
Stainless Steel	-2.24

At the termination of Test 40, ATL-307 had undergone a viscosity increase of only about 14 percent. The viscosity reference temperature utilized for ATL-307 was 210°F. However, because of its excessive deposit forming tendencies coupled with its corrosive action, ATL-307 must be considered unsatisfactory at temperatures of 650°F sump and 700°F test bearing.

Test 41 (Table 112), the second bearing test conducted with ATL-307, was scheduled for a sump temperature of 500°F and a test bearing temperature of 550°F. However, it developed during testing that the test bearing temperature exceeded 550°F without the benefit of external heating. Thus, it was impossible to control the temperature of the test bearing at 550°F. The test was allowed to continue with the test bearing temperature averaging 588°F throughout the 48-hr test period.

Shortly following the actuation of the bearing machine drive motor, it became apparent that Test 41 would also have an elevated test bearing stabilization temperature. This temperature reached a maximum of

468°F, and again required waiver of the usual stabilization temperature maximum of 375°F. Excluding test bearing temperature, test apparatus performance was satisfactory throughout the test. During the final 16 hours of operation, the test bearing temperature reached a maximum of 605°F.

Interim inspections of deposit accumulation within the bearing machine indicated that the heaviest deposit buildup came about during the final 16 hours of operation. At the completion of the test, the bulk test oil was dark brown in color, and it appeared that a small-particle suspension was the responsible factor. The sump wall and bottom were completely coated with a brown substance. A similar deposit, somewhat less thick, covered entirely all metal surfaces submerged in the test lubricant. In both cases, this deposit could be removed by moderate wiping.

In view of the apparent corrosive behavior of ATL-307 as indicated by Test 40, the test bearing used in Test 41 was weighed prior to and following testing. The following weight losses were observed:

	Weight, g	
	Outer Race	Inner Race-Cage Assembly
Before test	547.1173	890.5211
After test	546.4728	889.2052
Loss	0.6445	1.3159

Considerable pitting and corrosion occurred on the inner and outer races. However, the metal specimens in the sump showed no significant weight changes at a 500°F sump temperature.

The oxidative stability of ATL-307 at temperatures of 500°F sump and 588°F test bearing was evidenced by a very low test oil consumption rate and a viscosity increase of only 6.3 percent. Also, there was no significant test oil loss by evaporation as attested to by the fact that no condensed vapors were recovered by the vent trap. The filter screen elements were found to contain only small amounts of deposits. The recorded weights do not reflect actual deposits since residual test fluid remained on the elements after the specified drain period at 185°F. Unfortunately, the excellent oxidative stability of the fluid is overshadowed by its high apparent corrosivity, which is not adequately reflected by the high overall deposit rating (111.8) because, as described previously, the "deposits" were mostly not of the usual carbonaceous types but appeared to be essentially corrosion products. ATL-307 is

the only fluid evaluated in the entire present program that affected all standard metal test specimens and the only one that attached both titanium and stainless steel.

h. Test Results on ATL-401

Lubricant ATL-401 was initially investigated at two temperature conditions assigned by RTD. Test 56 (Table 117) was conducted at a sump temperature of 475°F and a bearing temperature of 575°F. At these temperatures, the performance of ATL-401 appeared very satisfactory with respect to deposit formation. The overall rating for this test was 43.5 and, in particular, the conspicuously low level of deposits formed on the test bearing was quite impressive. Because of viscosity increase, it was necessary to renew the test oil charge following 27 hr of testing. The five metal specimens from this test showed no evidence of corrosion at the sump temperature of 475°F.

The second test with ATL-401 (Test 58, Table 115) was conducted at a lower sump temperature of 425°F while maintaining the test bearing temperature of 575°F. As was expected, the decrease of the sump temperature resulted in a lower rate of degradation for lubricant ATL-401. The improvement was such that the initial test oil charge did not attain a 100 percent viscosity increase until reaching 44 hr of testing, at which time the test was terminated. Also, as has been the case with other fluids[1], the increase in temperature differential between the sump and bearing resulted in an increase in deposit formation which was reflected by the overall rating of 62.7. This combination of test temperatures effected, in small quantities, the formation of carbon deposits of the blistered and flaked varieties on the heater mount front and rear surfaces. The test bearing, however, continued to show a low level of deposit formation. At the direction of RTD, in addition to the standard five-metal specimens, magnesium and copper specimens were also included in Test 58. It was found that at the sump temperature of 425°F, the copper specimen underwent a weight loss of 1.2 mg/cm^2, while the magnesium sample sustained a weight loss of 0.3 mg/cm^2. The standard metal specimens gave no indication of experiencing corrosion.

This test was later followed by an additional evaluation of ATL-401 at these same test temperatures. While the earlier test (Test 58) included additional metal specimens of magnesium and copper, Test 70 (Table 114) was performed with only the standard five-metal specimens. The data obtained for Test 70 were in very good agreement with those recorded for Test 58, suggesting that the presence of magnesium and copper specimens has no observable effect on the deposit and degradation behavior of ATL-401. By comparison, Test 58 resulted in an overall rating of 62.7 while Test 70 was rated at 56.8, and both tests were terminated following 44 hr testing

because of test oil viscosity increase. Thus, satisfactory capability of lubricant ATL-401 at test temperatures of 425°F sump and 575°F test bearing, with less than 3 oil changes, is further substantiated.

Test 78 (Table 116) was also conducted with lubricant ATL-401 at temperatures of 425°F sump and 575°F test bearing. During testing, however, 1 cfm of water-saturated air was introduced into the sump to explore effects of such action upon ATL-401 performance. The test data, summarized in Table 47, indicate that this introduction of air into the lubricant sump did not significantly affect the deposit behavior of ATL-401. It does, however, show an obvious influence upon the degradation and consumption rates. Table 47 offers a ready comparison of Test 78 and the results from tests where no air flow to the sump was employed. The resulting acceleration, by approximately 50 percent, in both the degradation and consumption rates can be attributed to the action of air flow in the sump. Deposits data for ATL-401 testing at the above-mentioned temperatures show very good agreement with or without air flow in the sump. Therefore, in spite of the significant increase in consumption and degradation rates, lubricant ATL-401 is capable of satisfactorily meeting, at these test conditions, the minimum performance standards set by RTD.

Subsequent testing with lubricant ATL-401 was performed at 525°F sump and 575°F test bearing temperatures. Elevation of sump temperature brought about an expected acceleration in the degradation and consumption rates of ATL-401. Consequently, it was necessary in the course of this test (Test 71, Table 119) to replace the test oil charge three times, and test termination was required at 47 hr. Test oil consumption rose to a considerable 283 ml/hr. The overall rating determined for this test was 56.8, and on the basis of this value the deposit forming level of ATL-401 remained acceptable. The degradation rate, however, appears to be outside the acceptable limit.

Therefore, maintaining a 575°F test bearing temperature, an evaluation was conducted with ATL-401 at a sump temperature of 500°F. From this test (Test 73, Table 118) the less strenuous effect of the lower sump temperature upon the degradation and consumption rates is quite apparent when compared to performance at the 525°F sump temperature. At a 500°F sump temperature, ATL-401 consumption is approximately 85 ml/hr less than at 525°F. Thus the 500/575°F temperature combination appears to be well within ATL-401 capability.

The deposit profile for ATL-401 suggests that similar overall deposit ratings will be obtained at a bearing temperature of 575°F whether the sump temperature be 50 or 150°F lower. This behavior is a departure from the patterns established by previously examined lubricants. In addition, test results indicate that test temperatures of 500°F sump and

TABLE 47. COMPARISON OF BEARING TEST RESULTS ON LUBRICANT ATL-401

Test No.	58	70	78
Rig No.	1	2	2
% Vis increase, 100°F			
16 hr	38.4	43.3	58.6
32 hr	72.3	76.4	24.3[(b)]
48 hr	100.3[(a)]	98.7[(a)]	71.0
Net oil loss, ml/hr	73	79	116
Overall deposit rating	62.7	58.6	67.6
Metal specimens	7	5	5
Air flow to test oil sump, cfm	0	0	1

Sump temp, °F	425
Bearing temp, °F	575
Air flow to test oil sump, cfm	0.35

(a) Test terminated after 44 hr due to viscosity increase.

(b) Test oil changed at 28 hr due to viscosity increase.

575°F test bearing will provide the most satisfactory combination of deposit and degradation performance. Throughout ATL-401 testing, the standard metal specimens failed to show evidence of corrosion.

i. Test Results on ATL-402

Two tests were completed on lubricant ATL-402. The initial test (Test 67, Table 120) was performed at a sump temperature of 500°F and a test bearing temperature of 550°F. This temperature environment resulted in a very satisfactory overall deposit rating of 39. The bearing from this test was quite clean with the inner race having accumulated the only sludge present on the bearing while light and medium varnish comprised the greatest portion of deposit formation. Particularly unusual was the total absence of deposits from the heater mount front surface. Heretofore, this item has always been a major contributor to the overall deposit rating of a test, whether that rating was large or small. Degradation-wise, the lubricant performed well at a sump temperature of 500°F requiring a single test oil renewal, because of viscosity increase, after 27.5 hr of testing. Moderate oil consumption and noncorrosive behavior upon the metal specimens was observed for ATL-402 at a sump temperature of 500°F.

In view of this satisfactory performance at the aforementioned test temperatures, ATL-402 was investigated at higher temperatures of 525°F sump and 575°F test bearing (Test 68, Table 121). The 25°F increase in sump temperature resulted in a proportional increase in test oil consumption and degradation rates. Deposit formation, however, increased by an unexpectedly large amount resulting in an overall rating of 103.8. By far, the test bearing was responsible for the largest percentage of the marked increase in deposit rating.

Thus, 550°F would appear to be the maximum bearing temperature at which lubricant ATL-402 may be satisfactorily utilized, while a sump temperature up to and including 525°F can be expected to yield an acceptable rate of degradation. Also, at this temperature no discernible corrosion of metal specimens was detected.

j. Results on ATL-403

Only one test on candidate lubricant ATL-403 was performed. Investigation of this fluid was conducted at test temperatures of 500°F sump and 550°F test bearing (Test 69, Table 122). Beginning with the 16-hr interim inspection, indications were that a steady and considerable accumulation of sludge occurred as the test progressed. Thus, at the completion of this test, the bearing machine was found to be well covered with deposits. In addition, the test oil sump components were completely

enveloped with deposits ranging from sludge to carbon. Particularly, the test oil pressure and scavenge pumps (located within the test oil sump) were totally coated with heavy carbon. The metal specimens from this test were found to have undergone the following weight gains:

Specimen	Weight Gain, mg/cm^2
Aluminum	1.0
Titanium	0.6
Silver	0.9
Steel	1.0
Stainless steel	0.6

Close examination of these specimens revealed that the weight increases were the consequence of fine-particle carbon deposition on the specimen surfaces. With respect to degradation, at 500°F sump temperature, ATL-403 required test oil renewal after 16- and 32-hr testing in order to complete the 48-hr test schedule. The extensive degree and severity of deposit formation are apparent from the deposit rating of 115.9 established for ATL-403 at the mentioned test temperatures. Thus, though the degradation performance of this lubricant can be considered acceptable, deposit forming behavior would classify ATL-403 as unsuitable for applications involving temperatures of 550°F and above.

k. Test Results on ATL-405

Two tests were performed with candidate lubricant ATL-405. Test 74 (Table 124) was carried out at a sump temperature of 425°F and a test bearing temperature of 575°F. The results of this test show that a 575°F bearing temperature is quite severe on ATL-405. At this temperature, deposit formation is great and extends throughout the test machine as indicated by the overall deposit rating of 166. In particular, deposits collecting upon the test bearing were quite heavy. At the sump temperature of 425°F, ATL-405 degradation and consumption were quite satisfactory; because of this, a subsequent test was performed maintaining the 425°F sump temperature and lowering the test bearing temperature to 500°F. This test (Test 75, Table 123) indicated that at 500°F, ATL-405 capability is probably not adequate by the minimum performance standard set by RTD. Though the satisfactory degradation and consumption behavior of ATL-405 at a 425°F sump temperature continued to be evident, deposit formation at the 500°F bearing temperature was such that an overall rating of 88 resulted. At best, the overall performance

of ATL-401 might be considered marginal at these latter temperatures. In neither of the ATL-405 tests was there detected corrosive action by the lubricant upon the metal specimens.

E. Conclusions

Data obtained for the 5P4E polyphenyl ether (F-1041) with the 100-mm roller bearing machine indicate that satisfactory performance, both from the standpoint of deposit formation and oil degradation, could be expected of this lubricant at sump temperatures up to 600°F and bearing temperatures up to 650°F, requiring no intermediate oil change for the 48-hr test schedule. The rated items remained exceptionally clean throughout, yielding low deposit ratings at these temperatures. Also, the moderate viscosity increase, together with no change in neutralization number, displayed by F-1041 after completing the 48-hr test schedule established that excellent performance of this lubricant can be expected at these temperature conditions.

At a test bearing temperature of 700°F, F-1041 shows more significant overall deposit formation. Small amounts of the severe deposits, chiefly smooth and flaked carbon, were noted in these tests. At this bearing temperature, test oil degradation can be controlled by the sump temperature. With the test bearing maintained at 700°F, approximately 10, 25, and 60+ percent viscosity increase resulted with sump temperatures of 500, 600, and 650°F, respectively. Results indicate that F-1041 under these operating conditions can be considered marginal in performance.

In the case of the most strenuous temperature environment, 700°F test oil sump and 750°F test bearing temperature, F-1041 gave considerable amounts of carbon deposits of a smooth, crinkled, and flaked nature. At 600°F sump and 750°F bearing temperature, the oil deterioration was moderate, but the deposits encountered were the severest for all tests with F-1041. For the temperature conditions of 700°F sump and 750°F bearing, the lubricant deteriorated rapidly and did not complete the 48-hr test duration without intermediate oil changes. It must, therefore, be concluded that F-1041 did not provide satisfactory performance at any of these temperature environments.

In general, the addition of air to the sump did not give rise to any recognizable trend in the F-1041 tests. It did, however, result in higher test oil consumption rates through entrainment of oil vapors in the air stream passing out the sump vent.

The return of test oil recovered by the vent trap to the test oil system resulted in data compatible with that obtained for tests where only unused oil was introduced into the sump. The recirculation of recovered test oil showed no particular effect or undesirable influence on the F-1041 tests.

Results with the five-metal specimens indicate that F-1041 had no particular corrosive effects upon aluminum, titanium, silver, steel, and stainless steel at any of the aforementioned test conditions.

Investigation into test machine bias and test repeatability on deposit formation with F-1041 resulted in confirmation of previous efforts with other lubricants which showed the test machines to be rating uniformly and that test reproducibility for deposits was good. Though the rates of lubricant degradation, as measured by the viscosity increase, for the tests involved had a rather large spread, they did exhibit a similar trend. In view of past experience this condition is likely to occur without any obvious cause, or noticeable effect upon the deposit-forming tendencies of the test fluid.

Test lubricant ATL-304 was found to give satisfactory performance with respect to deposit formation at test temperatures of 500°F sump and 550°F test bearing. The rate of viscosity degradation was such that the test oil system required two recharges to complete the test. The deposit behavior of ATL-304 under these test temperatures was comparable to that of F-1041 at a sump temperature of 600°F and a test bearing temperature of 650°F. The degradation rate for ATL-304, however, was quite high when compared to the rate of deterioration of F-1041. At test temperatures 100°F higher, F-1041 undergoes a viscosity increase of approximately 10 percent for the same period of testing.

The tests utilizing lubricant ATL-305 revealed that this fluid could be expected to give highly acceptable performance with regard to deposit formations at test temperatures of 500°F sump and 550°F test bearing. However, as a result of its extremely rapid degradation rate, ATL-305 required three complete oil changes in completing the 48-hr test schedule. Thus, the excellent deposit behavior at these temperatures was somewhat depreciated by the poor degradation performance of ATL-305.

By lowering the sump temperature to 475°F while increasing the test bearing temperature to 575°F, the overall performance of ATL-305 was brought within acceptable limits. Thus, it appears that at bearing temperatures of 575°F and less, this lubricant will exhibit satisfactory deposit behavior. On the basis of acceptable degradation rate, the upper temperature tolerance of ATL-305 seems to be 475°F as approximately 20-hr test time can be achieved at this temperature before viscosity increase requires renewal. When compared to 5P4E capability, ATL-305 performance at temperatures of 475°F sump and 575°F test bearing is similar to that of F-1041 at corresponding temperatures of 650°F and 700°F. During the tests conducted with lubricant ATL-305, no corrosive action by the lubricant upon the metal specimens was encountered.

The suitability of lubricant ATL-307 for high-temperature applications is questionable. Certainly at the more strenuous test environment, namely 650°F sump and 700°F test bearing temperatures, ATL-307 could not satisfy minimum performance requirements. Deposit formation at these temperatures was not only excessive but consisted of the severest types as well. In addition, since the rapid, excessive, deposit buildup occurred so early in the testing, the observation that ATL-307 is unsuitable for use at the temperatures indicated appears justified. In addition, evidence from both ATL-307 tests indicates that above 500°F this lubricant has a corrosive action upon titanium and stainless steel.

From the data obtained with O-62-25, it is evident that the maximum test bearing temperature at which an acceptable deposit rating can be obtained is 475°F. In conjunction with this bearing temperature, a sump temperature of 450°F will give an acceptable rate of degradation for O-62-25. The stability of this lubricant can be greatly enhanced by lowering the sump temperature to 425°F while maintaining the 475°F test bearing temperature.

The series of repeat tests evaluating lubricant O-62-25 resulted in overall deposit ratings whose spread suggested bearing machine No. 1 rated less severely than machine No. 2. However, in view of the previously established test reproducibility, the later repeat tests with H-1001, and the lack of other evidence supporting existence of any significant difference between the two test machines, it is possible that this somewhat significant spread is attributable to the degradation characteristics of the lubricant rather than to the bearing machines. At all sump temperatures employed in the evaluation, O-62-25 had no observable corrosive effect upon the metal specimens. The deposit behavior of O-62-25 at 425°F sump and 475°F test bearing resembles that of the 5P4E polyphenyl ether at temperatures of 600°F sump and 650°F test bearing.

The study of lubricant H-1001 indicates that the maximum test bearing temperature at which this fluid is capable of satisfactory performance is 575°F. In combination with this bearing temperature, a maximum sump temperature of 525°F is apparently satisfactory. At these temperatures, H-1001 appears to have deposit-forming tendencies just slightly better than those of 5P4E at temperatures of 650°F sump and 700°F test bearing. However, the rate of degradation of H-1001 is not as consistent. During the repeat studies a substantial variation in degradation rates was recorded for the lubricant. Also, it was demonstrated clearly that water-saturated air flow of 1 cfm to the test test oil sump will induce a pronounced acceleration of bulk test oil degradation on H-1001.

Present state of investigation points to test bearing tolerances as the responsible factor for cage wear occurring throughout this testing. Test bearing cage assemblies have been found to have nonuniform internal diameters

varying by 0.002 to 0.005 inch. Also, inasmuch as cage wear, to varying degrees, was detected using lubricants other than H-1001, the lubricant does not appear to be the primary factor of the test bearing failures encountered.

Testing of candidate lubricant ATL-401 indicates that at 575°F test bearing temperature, this fluid will give acceptable performance. In conjunction with this bearing temperature, a sump temperature of 500°F will result in a very satisfactory level of deposit formation while the degradation rate will necessitate a renewal of test oil charge after approximately 20 and 40 hr testing. The degradation rate can be improved significantly by lowering the sump temperature to 425°F. This gain, however, is countered somewhat by an increase in deposits when the differential between sump and bearing temperature is so increased. Investigation also points to corrosive action of ATL-401 upon copper and magnesium as evidenced by the significant weight losses of these samples in testing. The five standard metal specimens did not indicate observable corrosion. Further, testing of lubricant ATL-401 reveals that the addition of copper and magnesium specimens to the standard 5-metal group has no apparent influence upon this lubricant's deposit and degradation behavior at temperatures of 425°F sump and 575°F test bearing. Water-saturated air flow to the test oil sump at these same temperatures has no detectable effect upon the deposit behavior of ATL-401; however, the deterioration rate is significantly accelerated. The deposit behavior of ATL-401 at 500°F sump and 575°F test bearing falls into the performance category of 5P4E at temperatures of 600°F sump and 650°F test bearing.

The abrupt increase in deposit formation when elevating test bearing temperature from 550°F to 575°F in ATL-402 testing would exclude the latter temperature as being within the realm of ATL-402 capability. Therefore, the maximum test temperature combination at which this lubricant can be expected to perform acceptably would appear to be 525°F sump and 550°F test bearing. ATL-402 displayed a noncorrosive behavior toward the standard metal specimens and, with respect to deposit formation, performed on the level of 5P4E at temperatures of 600°F sump and 650°F test bearing.

The single evaluation of lubricant ATL-403 established that a test bearing temperature of 550°F is beyond the successful range of ATL-403 performance. The 500°F sump temperature, however, would appear to result in an acceptable level of degradation for the lubricant. Metal specimens from this test all showed significant weight gains that were a consequence of particle deposition on the specimens submerged in the test lubricant.

Limited testing conducted on ATL-405 resulted in eliminating 575°F test bearing temperature as being within the capability of the lubricant. The performance at 500°F test bearing temperature was marginal, and an additional

evaluation at this temperature would be desirable before final judgement is made. The sump temperature of 425°F appears to be within ATL-405 capability and it seems likely that the upper limit for sump temperature is somewhat beyond 425°F. In neither of these tests was there any evidence of ATL-405 attack upon the metal specimens.

The evaluation of O-64-13 failed to provide a set of temperature conditions which were within successful capability of the lubricant. Tests were conducted at a bearing temperature of 575°F and sump temperatures of 425 and 525°F. All tests resulted in deposit ratings well beyond the limits set by RTD, though the 425°F sump temperature resulted in an acceptable rate of degradation. Observations fail to show O-64-13 corrosive toward the standard metal specimens.

IV. GEAR LOAD-CARRYING CAPACITY

A. General Remarks

The objectives of the gear load-carrying capacity phase of the program were to develop apparatus and techniques for determining the load-carrying capacity of lubricants at high temperatures and to evaluate the gear load-carrying capacity performance of candidate lubricants under environmental conditions representative of Mach 2.5 to 3 class gas turbine engine designs.

During the present reporting period, the gear load-carrying capacity of candidate lubricants at 165, 400, 500 and 600°F temperature conditions was determined. Additional tests were also made on several lubricants evaluated during the first year of the program in order to define more accurately the trend of variation of load-carrying capacity with test gear temperature. The results obtained have established beyond doubt the previously reported trend[1] that, as the gear temperature is progressively increased, the load-carrying capacity decreases until a minimum is reached, after which it increases with further increase in temperature. For the lubricants evaluated in this program, the temperature at which minimum load-carrying capacity is obtained varies in the range of 400 to 500°F, being apparently a function of lubricant composition.

In addition to this gear load-carrying capacity determination, dynamic calibration of the load system of the WADD high-temperature gear machine was extended to speeds of 15,000 and 20,000 rpm. These results, together with those obtained at speeds up to 10,000 rpm,[1] have served to confirm that proper loading was achieved in the WADD high-temperature machine at speeds up to 20,000 rpm.

The effects of test lubricant flow rate and the volume of test lubricant used in the recirculating test oil system were also investigated. An increase in test oil flow rate was found to result in an increase in gear load-carrying capacity, with some indication of improved test repeatability. An increase in test lubricant volume was found to decrease lubricant deterioration during a high-temperature test, further confirming that the increase in gear load-carrying capacity at high temperatures is due partly to degradation of the bulk lubricant and partly to formation of lubricant deposits on the gear teeth.[1]

B. Test Equipment and Techniques

1. WADD High-Temperature Gear Machine

Two WADD high-temperature gear machines, previously described[1], were used for the work reported herein. No changes in design, operating principle, or instrumentation were made. The gear machines have accumulated approximately 1100 hours of trouble-free operation since the diametral clearance of the support roller bearings was increased from 0.0005 inch to 0.0030 inch.

2. Test Oil and Support Oil Systems

It was necessary to replace the test oil pump drive system, motor and control, due to failure and obsolescence of the test oil pump drive motor heretofore used on the 1/2-liter test oil system. For the purpose of congruity, the test oil pump drive system is now the same as that used on the test oil systems of the 100-mm bearing machines[1]. Some modification of the test oil sump cover and method of mounting the sump were necessary to accommodate the new test oil pump drive system. Since these changes were all external to the test oil system, it is not expected that they would have any effect on gear load-carrying capacity results.

No changes in design or operating principle of the support oil system, previously reported[1], were required for the work reported herein.

3. Load System

A method was devised to remove automatically the gear tooth load during a test in the event of an undetected decrease in test oil pressure. An automatic device has always been used to shut down the machine in the event of a failure in test oil pressure, but it was necessary for the operator physically to remove the load on the test gears. Usually by the time the operator is aware of the failure and takes action to remove the load on the gears, severe scuffing has already occurred. Consequently, a set of test gears is usually destroyed along with the loss of a test. By the use of two solenoid-operated valves and a pressure-sensitive switch, a slight decrease in test oil pressure causes one solenoid valve to shut off the supply of air to the pneumatic load valve, while at the same instant the other solenoid valve drains the air pressure from the diaphragms of the valves. In this manner, then, the gear tooth load is removed entirely or considerably reduced before lubrication is completely lost.

4. High-Temperature Test Gears

Nitralloy N steel test gears were used in the high-temperature load-carrying capacity work described herein. A detailed description of these test gears has been previously given[1]. No changes in design or principal dimensions were required for this work. The principal dimensions of the high-temperature test gears are shown in comparison with those of the standard Ryder test gears in Table 48.

5. Heating, Measurement, and Control of High-Temperature Test Gears

The high-temperature test gears were heated by induction heating and the gear-blank temperature was measured and controlled with an infrared radiometer-recorder-controller system. A block diagram of the system is shown in Figure 17. These systems, previously described[1], have continued to give satisfactory performance.

C. Test Procedures

1. High-Temperature Load-Carrying Capacity Tests

The procedure used in the high-temperature load-carrying capacity studies differs only slightly from Federal Test Method 6508 in that a different machine (WADD high-temperature gear machine), special test gears, and induction heating of the test gears are used. A comparison of the two test methods is shown in Table 49. The specific WADD high-temperature gear machine operational procedure has been previously described[1]. No changes in this procedure were required for the work reported herein.

2. Gear Machine Calibration

The procedure, apparatus, and technique used in the calibration of the WADD high-temperature gear machine has been previously described in detail[1]. In the calibration work reported herein, the test gear speed rather than test gear temperature was varied.

D. Test Results and Discussion

1. High-Temperature Test Results

Including the earlier work[1], the load-carrying capacities of 15 selected lubricants were determined, with the Nitralloy N steel test gears, at test gear temperatures of 165, 425, 500, and 600°F. The load-carrying

TABLE 48. COMPARISON OF PRINCIPAL DIMENSIONS OF STANDARD RYDER TEST GEARS WITH HIGH-TEMPERATURE TEST GEARS

	Standard Ryder Test Gears	High-Temperature Test Gears
Pitch Diameter, in.	3.500	3.500
Face Width, Narrow Gear, in.	0.250	0.250
Face Width, Wide Gear, in.	0.937	0.375
Number of Teeth	28	28
Diametral Pitch	8	8
Pressure Angle, degree	22.5	22.5
Tip Relief	None	None
Material	AMS-6260	Nitralloy N
Case Hardness, Rockwell 15 N	90-92	90-92
Case Thickness, in.	0.025-0.040	0.018-0.024
Core Hardness, Rockwell C	30-40	30-40
Surface Finish, rms, in.	$20\text{-}35 \times 10^{-6}$	$20\text{-}35 \times 10^{-6}$
Backlash, in.	0.002-0.006	0.011-0.014

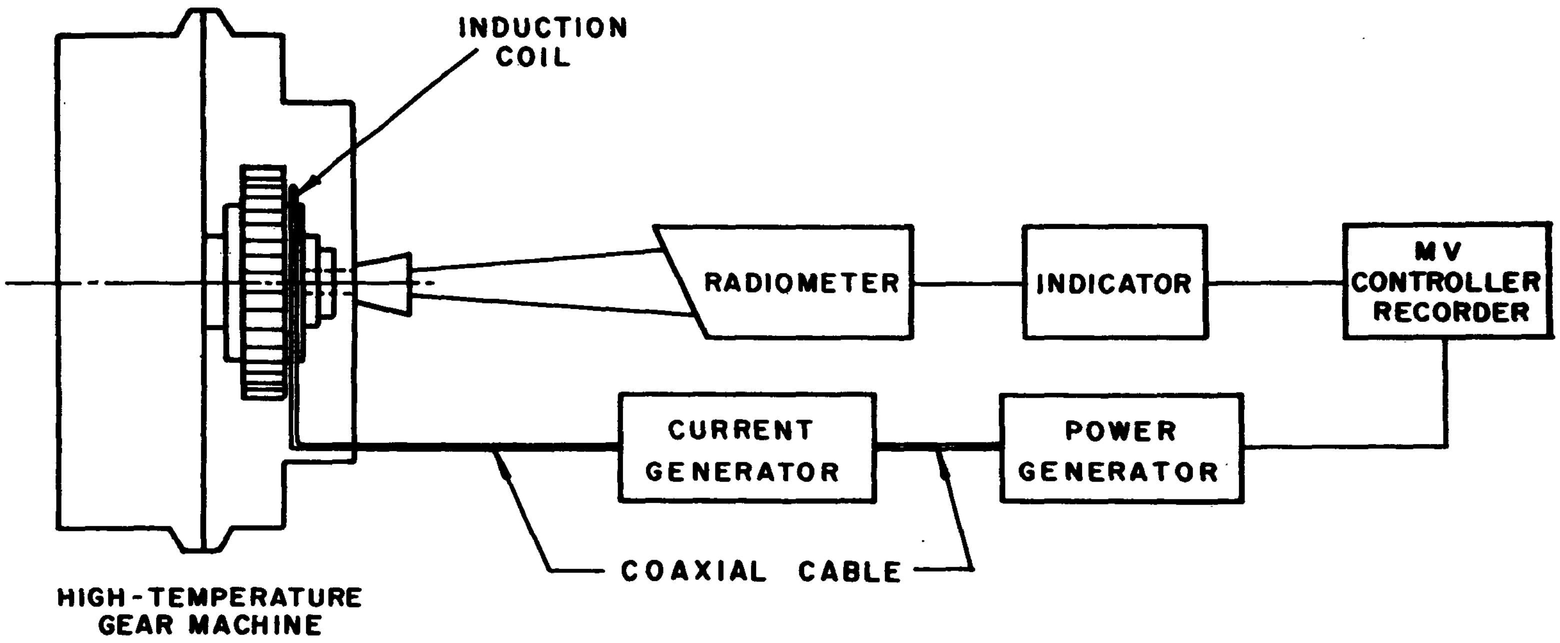

FIGURE 17. INDUCTION HEATING CONTROL SYSTEM

TABLE 49. COMPARISON OF LOAD-CARRYING CAPACITY TEST METHOD

	Federal Test Method 6508	Methods Used in Present Program	
		165°F Test	≥ 400°F Test
Test Machine	Erdco-Ryder gear machine	WADD high-temperature gear machine	WADD high-temperature gear machine
Test Gears	Ryder test gears	Special Nitralloy N test gears	Special Nitralloy N test gears
Operating Conditions			
Test gear speed, rpm	10,000 ± 10	10,000 ± 100	10,000 ± 100
Test oil flow rate, ml/min (exit lubrication)	270 ± 5	270 ± 5	270 ± 5
Test oil-in temperature, °F	165 ± 5	165 ± 5	400 ± 5
Support oil-in temperature	165 ± 5	165 ± 5	165 ± 10
Test Gear Temperature	Not controlled	Not controlled	Controlled at required test temperature
Method of Loading			
Increment steps in tooth load (corresponding to 5-psi steps in load oil pressure), lb/in.	370	230	230
Duration of load-increment steps, min	10	10	10
Criterion of Lubricant Rating	Tooth load at which 22.5% of working tooth area is scuffed	Tooth load at which 22.5% of working tooth area is scuffed	Tooth load at which 22.5% of working tooth area is scuffed

capacity of one lubricant, O-61-20, was also evaluated at 700°F. The 15 lubricants included one 5P4E polyphenyl ether (O-61-20), one 4P3E polyphenyl ether (LRO-8), two MIL-L-9236 lubricants (MLO-61-1011, O-60-26), two polyglycols (GTO-770, E-1022), two silicones (GTO-615, G-1049), two mineral oils (Ref. Oil B, F-1055), and five candidate lubricants (O-64-13, ATL-304, ATL-305, H-1001, H-1026). LRO-8 was evaluated at only 165 and 425°F due to the limited amount of this test oil available to the program.

The individual load-carrying capacity results obtained are presented in Table 50 along with the results reported earlier[1]. Table 51 presents these data in summary form. A plot of the average load-carrying capacity versus test gear temperature is shown in Figure 18. As can be seen, the load-carrying capacity of all the lubricants evaluated in the program decreased as test gear temperature was increased from 165 to 400°F. In the 400 to 500°F test gear temperature region, a minimum load-carrying capacity value was obtained for all lubricants evaluated; and a further increase in test gear temperature resulted in increased load-carrying capacity for each lubricant. Also, it may be noted that the minimum load-carrying capacity did not occur at the same gear temperature for all lubricants. For example, with the silicone lubricant GTO-615, and candidate lubricant H-1001, the minimum point occurred at approximately 500°F. In all other cases, the minimum points were in the range of 400 to 425°F.

High-temperature load-carrying capacity evaluations were made on two lubricants, ELO-63-70 and ATL-307, not included in the previously mentioned data due to the limited number and type of tests performed. The scuff-limited load procedure used in these evaluations differed from the regular high-temperature load-carrying capacity procedure in that, in addition to the regular cleaning procedure, a special flushing procedure was used as directed by RTD.

The evaluations on ELO-63-70 were made at 425°F test conditions only. The results obtained were as follows:

	Load-Carrying Capacity, lb/in.	
	A_1	A_2
	4450	4860
Average	4660	

Due to the nature of the scuff failure obtained, two sets of test gears were required to obtain the two determinations. The "A" side of the

TABLE 50. SUMMARY OF INDIVIDUAL LOAD-CARRYING CAPACITY DETERMINATIONS OBTAINED USING NITRALLOY N STEEL TEST GEARS

	Load-Carrying Capacity, lb/in.													
	Test Gear Temperature, °F													
	165		300		400		425		500		600		700	
Oil Code	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Ref. Oil B	5280(a)	-					4740	5030	5550	(b)				
	5400	5380					4930	3700	5440(a)	5560(a)				
	5350						4600		5520					
E-1022	3670	2620					2480	2100			3250	2970		
							1850	-						
	3150						2140				3110			
F-1055	4950	5280					3660	3900			4870	4970		
	4530	4760					3760	-						
	4880						3770				4920			
G-1049	2220	2050					700	890			1980	2220		
							450	630						
	2140						670				2100			
H-1001	2080	2080	1390	1390			330	820	560	630	1740	2070		
							850	940						
	2080		1390				740		600		1910			
H-1026	2070	2310					2300	1850	1880	1850	2500	2310		
							1360	1100						
	2190						1650		1870		2410			
GTO-615	2430	2340					1330	1260	700	720	1690	1360		
	2500	2380					1080	1130	590	870				
	2410						1210		720		1530			
GTO-770	5190	4430			3200	3880	3690	3730	4390	4090	>5600(a)	>5600(a)		
	5320	4750			4090	3620	4080	4320	3990	4370	>5600(a)	5490(a)		
	4920				3700		3960		4210		>5600			
LRO-8	2640	2570					1290	960						
	2440	2470					750	750						
	2530						940							
O-60-26	1920	(c)			550	570	1080	740	1530	820	1410	1370		
	1540	2060			520	610	1010	940	1010	980				
	1840				560		940		1090		1390			
O-61-20	2380	2430	2050	2170	980	1330	1040	1060	1220	1530	1560	1540	2740	3120
	2460	2560			1280	1350	1260	820	1360	1170	2200	2130	1810	2470
							1040	1040					2200	2080
	2460		2110		1240		1040		1320		1860		2400	
O-64-13	2290	2120					1220	1330	1810	1880	2440	2490		
	2210						1280		1850		2470			
MLO-61-1011	1640	2170			450	560	1000	530	470	1700				
	2040	1720			600	350	1690	220	570	1930				
							800	1090						
							680	1140						
							680	1590						
	1890				490		940		1170					
ATL-304	2090	2630					1740	2020	1960	2010	2620	2780		
	2280	2460					1740	2300	1610	2520				
							1250	2190						
	2370						1870		2030		2700			
ATL-305	2020	1850					1850	1780	1800	1920	2680	2630		
	1990	1800					940	1590						
	1920						1540		1860		2660			

WADD high-temperature gear machines with 0.0025-in. diametral support roller bearing clearance used for all determinations. Standard backlash (0.005 in.) test gears and conventional heating used for all determinations at 400°F and below. Increased backlash (0.011 in.) test gears and induction heating used for all tests above 400°F.

(a) Values obtained by extrapolation.

(b) Determination not made due to tooth breakage during "A" side determination.

(c) Determination lost due to failure in test oil system.

TABLE 51. SUMMARY OF AVERAGE LOAD-CARRYING CAPACITY RESULTS OBTAINED USING NITRALLOY N STEEL TEST GEARS

	Load-Carrying Capacity, lb/in.						
	Test Gear Temperature, °F						
Oil Code	165	300	400	425	500	600	700
Ref. Oil B	5350(3)			4600(4)	5520(3)		
E-1022	3150(2)			2140(3)		3110(2)	
F-1055	4880(4)			3770(3)		4920(2)	
G-1049	2140(2)			670(4)		2100(2)	
H-1001	2080(2)	1390(2)		740(4)	600(2)	1910(2)	
H-1026	2190(2)			1650(4)	1870(2)	2410(2)	
GTO-615	2410(4)			1210(4)	720(4)	1530(2)	
GTO-770	4920(4)		3700(4)	3960(4)	4210(4)	>5600(4)	
LRO-8	2530(4)			940(4)			
O-60-26	1840(3)		560(4)	940(4)	1090(4)	1390(2)	
O-61-20	2460(4)	2110(2)	1240(4)	1040(6)	1320(4)	1860(4)	2400(6)
O-64-13	2210(2)			1280(2)	1850(2)	2470(2)	
MLO-61-1011	1890(4)		490(4)	940(10)	1170(4)		
ATL-304	2370(4)			1870(6)	2030(4)	2700(2)	
ATL-305	1920(4)			1540(4)	1860(2)	2660(2)	

WADD high-temperature gear machines with 0.0025 in. diametral support roller bearing clearance used for all determinations. Standard backlash (0.005 in.) test gears used for all determinations at 400°F and below. Increased backlash (0.011 in.) test gears used for all tests above 400°F. Number in parentheses indicates number of determinations used to obtain average.

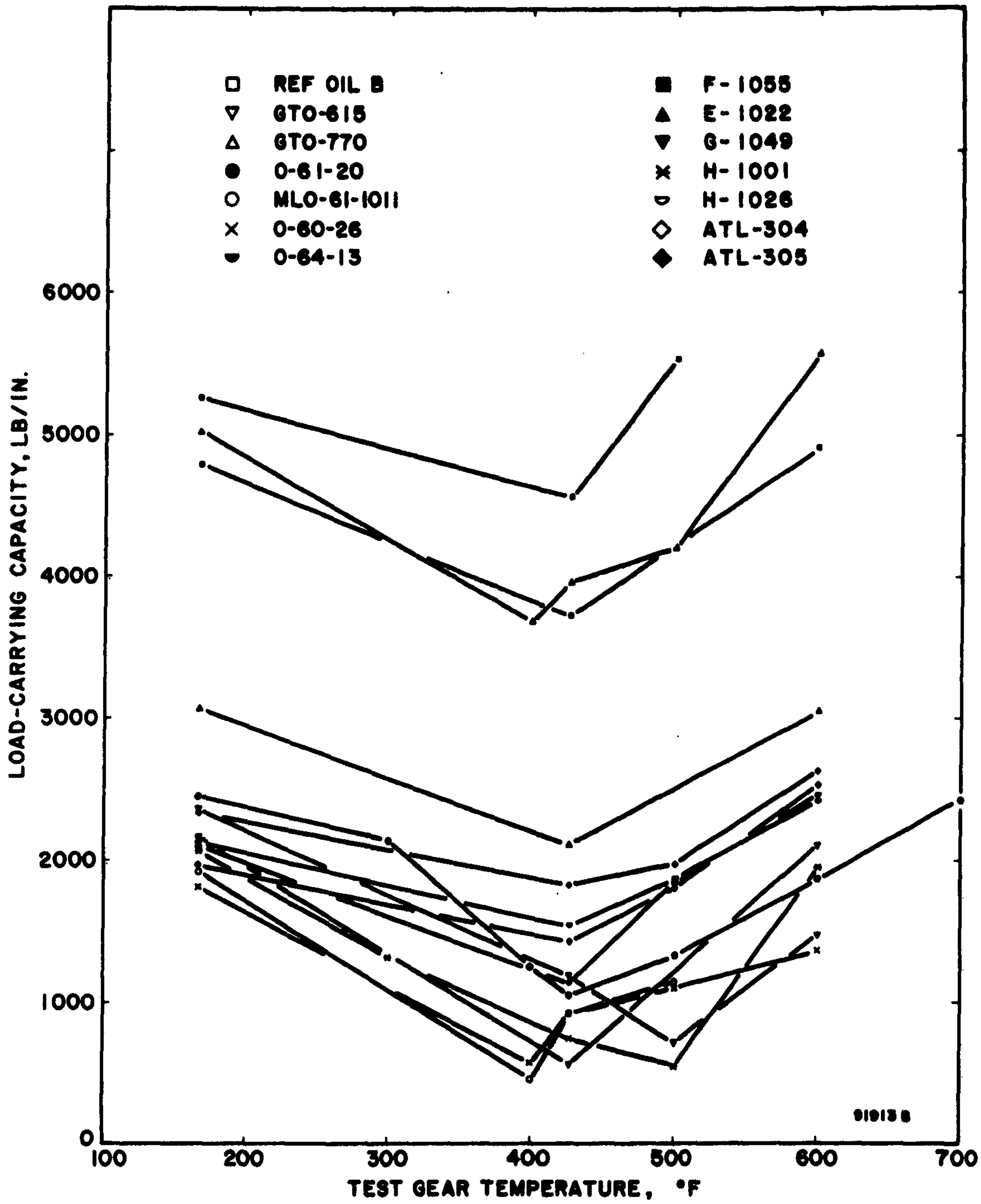

FIGURE 18. LOAD-CARRYING CAPACITY VERSUS TEST GEAR TEMPERATURE USING NITRALLOY N STEEL TEST GEARS

test gear was used in each case, and the test results are designated as "A_1" and "A_2". The load-carrying capacity failure in each case was very sudden, resulting in the destruction of approximately one-half of the teeth on both test gears due to tooth deformation and bending. In each of the determinations, the average scuff at the load previous to the failure load was 12.8 and 10.5 percent, respectively. At the failure load, an average of 65 percent scuff was obtained. At the load previous to the failure load, the induction heating of the test gears was required only to bring the test gears to the test temperature of 425°F. However, as the run progressed the test gears appeared to generate heat such that the temperature tended to increase slowly and uncontrollably to approximately 450°F with the induction heater in the off position. At the load at which failure occurred, the same slow and uncontrollable increase in gear temperature was noted for approximately three minutes of the run, at which time the gear temperature increased very rapidly to approximately 600°F. At this time the running attitude of the gears indicated that catastrophic failure had occurred and the run was terminated. The lubricant test section, including the test oil system, test gear cover, and the test gears, were found to be exceptionally clean and free of any deposits at the end of a determination. This state of a clean, deposit free test oil system has not been encountered with any other lubricant.

In view of the limited quantity of lubricant ATL-307, it was directed by RTD that the 425°F evaluation be made on a sample which had been used in a bearing deposit test. The used ATL-307 was filtered through No. 2 Whatman filter paper prior to use. The results obtained were as follows:

Load-Carrying Capacity, lb/in.

	A	B
	2540	2540
Average	2540	

The mode of failure of the used ATL-307 was similar to that of ELO-63-70, in that scuff failure occurred primarily during a single load increment. There was, however, no deformation or bending of gear teeth as with ELO-63-70, and induction heating was required throughout each of the load increments including the load increment at which 22.5 percent scuff was obtained.

It was requested by RTD that a single determination at the 425°F test condition should be made on new ATL-307 as a check on the results obtained on the used material. The load-carrying capacity obtained was 1160 lb/in. The mode of scuff failure was the same as that obtained with the used material.

In order to obtain additional indications of the load-carrying capacity of ATL-307, the "B" side of the gear was run, using the test oil from the "A" side determination above, according to the following schedule:

(1) At 400°F test-oil-in temperature and 425°F gear temperature, the test gears were step-loaded in the usual manner until scuff was obtained.

(2) The gear temperature was increased to 500°F and the step-load procedure repeated to the load at which an increase in scuff was obtained.

(3) The gear temperature increase was continued in 100°F increments and the step-load procedure repeated until a reasonable total average percent scuff was obtained.

The results obtained were as follows: At 425°F gear temperature, 2.7 percent scuff was obtained at 35 psig load oil pressure. At 500°F, an increase in scuff to 27.3 percent was obtained at the 10 psig load. At 600°F, an increase to 30.5 and 43 percent was obtained at the 5 and 10 psig load oil pressures, respectively. The gear tooth loads corresponding to the load oil pressures given above are: 425°F - 1630 lb/in.; 500°F - 470 lb/in.; and 600°F - 230 and 470 lb/in., respectively. From these results, it may be speculated that the load-carrying capacity for ATL-307 at gear temperatures of 500 and 600°F is approximately 470 and 230 lb/in, respectively.

2. Effect of High-Temperature on Load-Carrying Capacity

Though from the above studies, the lubrication mechanism involved cannot be derived, earlier work(1) has shown that with most lubricants the decrease in load-carrying capacity with gear temperatures up to the 400 to 500°F level may be due to a corresponding decrease in lubricant viscosity which, in turn, produces a greater amount of scuff at lower loads. At test gear temperatures above 400 to 500°F, depending upon the lubricant, it may be speculated that the original liquid lubricant plays a secondary role in the lubrication mechanism, while the primary role is being provided by the products of decomposition of the liquid lubricant. The increase in the amount of deposits on the test gears with an increase in test gear temperature was examined and reported previously(1).

As a means of investigating the effects of decomposition products in the liquid lubricant, 425°F scuff-limited load determinations were made with O-61-20 which had been used in a 700°F gear test. The results obtained

on this used oil are shown in Table 52 in comparison with results obtained at 425 and 700°F on new O-61-20. As can be seen, at 425°F test conditions, the load-carrying capacity obtained on the used unfiltered oil is approximately 70 percent higher than that obtained on new oil. Also, this value is approximately 25 percent lower than that obtained at 700°F on new oil. Though the data are limited, there is a definite indication that the decomposition products produced during a high-temperature test are involved both as deposits on the test gears as well as a suspension in the test oil bulk. As another means of showing the effect of the decomposition products suspension on load-carrying capacity, it was decided that if the used lubricant from the 700°F test were properly filtered such that these decomposition products were removed, the 425°F load-carrying capacity of the filtered lubricant should be the same as that obtained on the new oil at 425°F test conditions, assuming no large effect from bulk lubricant deterioration. Therefore, the lubricant was filtered repeatedly first through Whatman No. 2 filter paper and then through Millipore paper with 0.5 micron porosity. The resultant filtrate was clear and had a dark amber color. The load-carrying capacity obtained on the used, filtered oil as shown in Table 52 is still higher by about 50 percent than the average for new O-61-20 at 425°F test conditions, but lower by 12 percent than that obtained on the unfiltered, used oil. The lubricant drained from the sump at the end of the test had the same appearance as before filtration, i.e., black and opaque.

In practice, whether or not large amounts of lubricant deposits, with the attendant increased filter plugging tendency, etc., can be tolerated from the overall lubrication system standpoint needs, of course, to be carefully considered. However, in terms of load-carrying capacity alone, the observed phenomenon does have some significance. The fact that load-carrying capacity increases at gear blank temperatures beyond the 400 to 500°F range is not of great practical importance since any power transmission system operating at high temperatures must pass through the temperature range of minimum load-carrying capacity, 400 to 500°F. The important fact is that in the gear temperature range of 500 to 700°F, the load-carrying capacity is not likely to be lower than that obtained in the 400 to 500°F temperature range.

3. Test Method Correlation

It was shown earlier[1] that no general correlation existed when the load-carrying capacity results obtained using Nitralloy N steel gears at 165 and 425°F test conditions were compared with those obtained using standard Ryder test gears at 165°F test conditions. However, in the same report, it was shown that if the same gear material, namely Nitralloy N steel, was used, the load-carrying capacity results obtained at the two different

TABLE 52. EFFECT OF OIL DETERIORATION ON LOAD-CARRYING CAPACITY OF O-61-20

Test Oil	Load-Carrying Capacity, lb/in. 425°F A		425°F B	700°F A		700°F B
O-61-20	1040		1060	2740		3120
(New Sample)	1260		820	1810		2470
	1040		1040	2200		2080
		1050			2400	
O-61-20[(a)] (Used Sample, Unfiltered)	1730		1820			
		1780				
O-61-20[(b)] (Used Sample, Filtered)	1400		1730			
		1560				

WADD high-temperature gear machine with 0.0025 to 0.0035 in. diametral support roller bearing clearance used for all determinations. Increased backlash (0.011 to 0.014 in.) test gears used. Half-liter test oil system used.

(a) Lubricant was obtained from the last two determinations shown for 700°F.

(b) Lubricant was obtained from (a). Lubricant charge not changed between "A" and "B" side determinations due to limited amount of filtered lubricant available.

temperatures, 165 and 425°F, exhibited a consistent though nonlinear relationship, thereby suggesting that a degree of correlation may exist at these latter conditions.

Figure 19 represents a plot of the 165 and 425°F Nitralloy N steel gear data shown in Table 51. It appears from Figure 19 that a very general nonlinear relationship may exist over the range of load-carrying capacities exhibited by the lubricants included in the program. However, in the range of normal interest, 2000 to 3000 lb/in. load-carrying capacity, there does not exist a sufficiently definitive relationship which could be relied upon to predict accurately, from 165°F test information, the results which might be expected at 425°F test conditions.

4. Extended Time Test Results

In view of the rather large amount of deposits obtained on the test gears during 600 and 700°F gear temperature load-carrying capacity determinations, it was decided to investigate the effect of these deposits on the performance of the test gears during extended time operation at 700°F gear temperature. The lubricant used was 5P4E polyphenyl ether (F-1041). In order to keep the average percent scuff level low, a gear tooth load of 1180 lb/in. (25 psi load oil pressure), which is approximately the scuff-limited load of 5P4E at 425°F, was used. Because of the large oil consumption rate and the filter clogging experienced in the high-temperature tests with the 1/2-liter test oil system, it was decided to use a 2-gallon test oil system to prevent the possibility of gear scuff failure due to low test oil level or loss of test oil flow.

The test gears were heated to 700°F using the induction heater. The gears were loaded to 25 psi load oil pressure using the standard step-load procedure with gear scuff inspections following each 5-psi load increment. Two 6-hr constant-load (25 psi load oil pressure) runs were then made with gear scuff inspections following each 2-hr period.

The first high-temperature extended time test, using the 2-gallon test oil system, did not appear to produce the amount of deposits on the test gears that had previously been noted during high-temperature load-carrying capacity tests using the 1/2-liter test oil system. In addition, the average scuff at the end of the step-load portion of the test was higher than anticipated.

In view of the smaller amount of deposits on the test gears and the unexpected amount of scuff obtained when using the 2-gallon test oil system, it was decided to obtain load-carrying capacity data for the 5P4E polyphenyl ether at 700°F test gear temperature condition, using the 2-gallon test oil system. These data are discussed in detail in the next section of this report.

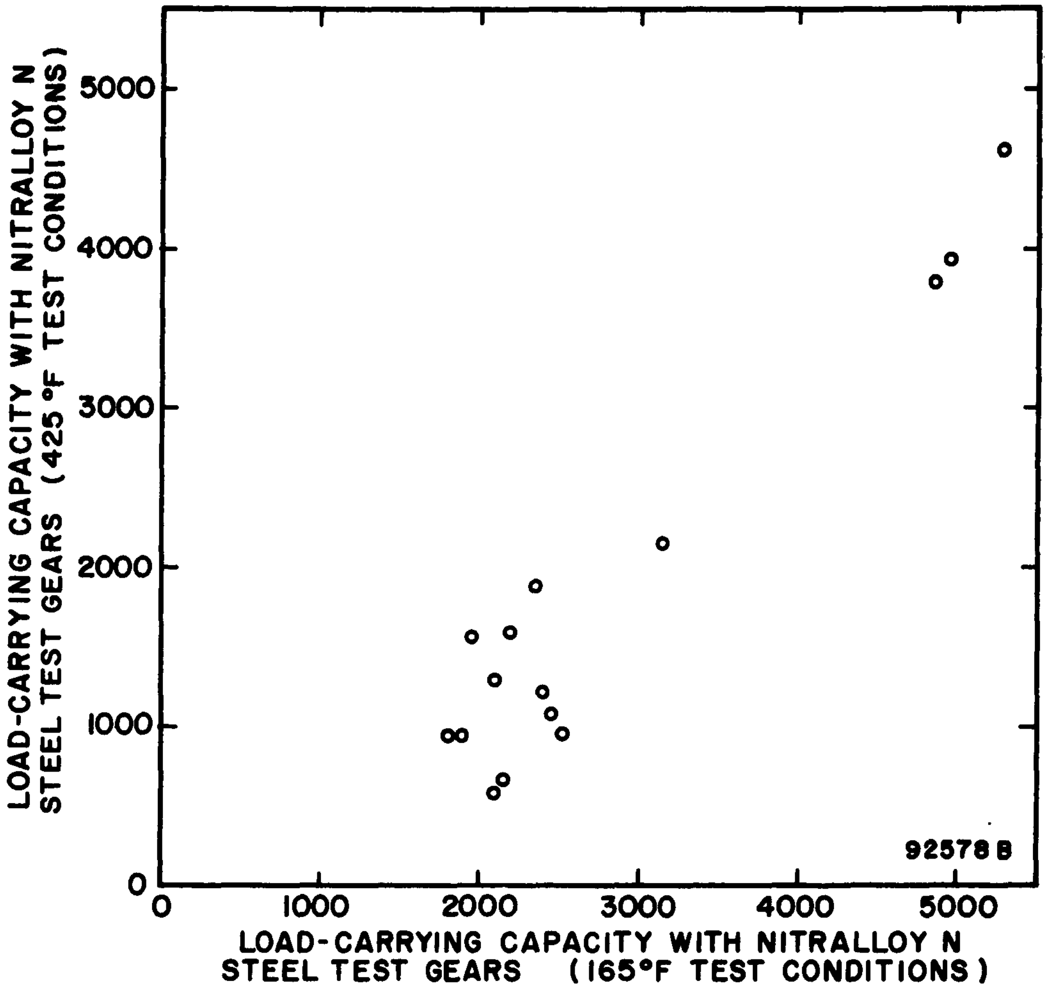

FIGURE 19. RELATION BETWEEN LOAD-CARRYING CAPACITY OBTAINED AT 165° F AND 425° F TEST CONDITIONS WITH NITRALLOY N STEEL TEST GEARS

However, a definite reduction in load-carrying capacity was obtained when the 2-gallon test oil system was used. Earlier studies, conducted at 400°F test conditions, showed no difference in load-carrying capacity when either system was used. However, it is evident from the present investigation that at some test gear temperature above 400°F, the test oil system volume somehow affects the load-carrying capacity results. This is possibly explained by the difference in concentration of the product of lubricant deterioration in the two test oils systems.

An extended time test at 700°F test gear temperature was next run using the 1/2-liter test oil system in an attempt to show a quantitative difference in test gear deposits between tests conducted using the two test oil systems. One additional extended time test was conducted using each of the two test oil systems. The results of these tests are presented in Table 53. Tests 1 and 3 were run on the A and B sides, respectively, of one set of test gears. Tests 2 and 4 were run on the A and B sides of a second set of gears. The test gears were cleaned between the A and B side tests in order that no carryover effect from the deposits formed during the A side test would affect the B side results. Test gear weights were taken before and after each test as a measure of the deposits acquired during each test. As will be noted in Table 53, no conclusive information is available, with the exception of the appearance and the viscosity of the oil samples taken at the end of the tests. Test 2, using the 2-gallon test oil system, showed a larger weight of deposits for the narrow test gear. However, visually, the deposits appeared to be about the same in quantity and appearance as those obtained in Test 1.

5. Effect of Test Oil Volume on Load-Carrying Capacity

In the preceding section of this report, it was indicated that the volume of test oil had an effect on the load-carrying capacity of the 5P4E polyphenyl ether at test conditions above 425°F. Therefore, load-carrying capacity determinations were made on O-61-20 at 700°F and on four additional lubricants at 600°F test conditions using a 2-gallon test oil system The results obtained at shown in Table 54, in comparison with results previously obtained on these lubricants with the 1/2-liter test oil system. As can be seen, the average load-carrying capacity obtained on lubricants O-61-20 and F-1055, using the 2-gallon test oil system, are considerable lower that the average obtained on these oils with the 1/2-liter system. With lubricants E-1022, O-60-26, and G-1049, the reverse is true. From these data, it may be assumed that test oil volume has an effect on the load-carrying capacity of different lubricants. It appears that the different lubricant types may be related to the fact that a change in test oil system volume alters the degree of degradation of the lubricants and possibly the amount and nature of the deposits formed on the gear teeth. However, the observations made to date do not warrant specific conclusions to be drawn. Further study of this effect is therefore indicated.

TABLE 53. EXTENDED TIME TEST RESULTS OBTAINED ON 5P4E POLYPHENYL ETHER AT 700°F TEST GEAR TEMPERATURE

	2-gallon Test Oil System		1/2-liter Test Oil System	
Test No.	1	2	3	4
Test duration, hr	6	6	6	6
Load, lb/in.	1180	1180	1180	1180
Deposit weight, g				
Narrow gear	0.184	0.709	0.359	0.390
Wide gear	0.112	0.218	0.192	0.531
Viscosity at 100°F, cs				
Initial	354.5	354.5	354.5	354.5
Final	365	364	367	372
Oil consumption, cc	3800[a]	3800[a]	3800	2500
Used oil appearance	(c)	(c)	(b)	(b)
Average scuff, %				
Initial	8.2	15.9	3.6	5.7
Final	10.5	58.8	13.7	30.0
Increase	2.3	42.9	10.1	24.3
Pitting	0	0	0	0

(a) Approximate values

(b) Very black, opaque

(c) Slightly black, translucent

TABLE 54. EFFECT OF LUBRICANT VOLUME ON LOAD-CARRYING CAPACITY AT GEAR TEMPERATURES ABOVE 500°F

	Load-Carrying Capacity, lb/in.			
	1/2-Liter		2-Gallon	
Oil Code	A	B	A	B
O-61-20[a]	2740	3120	1230	1390
	1810	2470	1580	1370
	2200	2080		
	2400		1390	
F-1055	4870	4970	4440	3930
	4920		4190	
E-1022	3250	2970	4200	(b)
	3110			
O-60-26	1410	1370	1380	1880
			1620	2540
	1390		1860	
G-1049	1980	2220	2810	3020
	2100		2920	

WADD high-temperature gear machine with 0.0025 in. diametral support roller bearing clearance used for all determinations. Increased backlash (0.011 in.) test gears used.

(a)Results shown were obtained at 700°F gear temperature. All others obtained at 600°F gear temperature.

(b)"B" side determination not obtained due to lubricant supply.

6. Effect of Test Oil Flow Rate on Gear Tooth Scuffing

The standard test oil flow rate of 270 ml/min has been used almost exclusively in the high-temperature test method development work. During this reporting period, experiments were initiated to study the effect of the flow rate variable on gear tooth scuffing. It was decided that these studies would be conducted at test gear temperatures of 425 and 600°F, two temperatures that are fairly widely separated and at which the major portion of the high-temperature work has been done. The procedure used in this investigation was as follows:

(1) With a test-oil-in temperature of 400°F, the test oil flow rate was adjusted to 1200 ml/min.

(2) The test gears were step-loaded, with the test gear temperature maintained at the desired temperature level, until approximately 5 to 10 percent average scuff was obtained.

(3) At the load attained in (2) above, the test oil flow rate was decreased, following each 10-minute run interval, from 1200 to 400 ml/min in increments of 200 ml/min; from 400 to 275 ml/min in one step; then from 275 to 50 ml/min in increments of 25 ml/min.

(4) Following each 10-minute interval, the narrow test gear was inspected for scuff increase.

The results obtained in the investigation of the effect of test oil flow rate on gear tooth scuffing are shown graphically in Figures 20 and 21. These results, especially those shown in Figure 20, show that generally for the lubricants with which large scatter in load-carrying capacity scatter is obtained, increases in gear tooth scuffing are obtained as test oil flow rate is reduced below 500 ml/min. These data also show that the reverse is true, i.e., for those lubricants with which slight load-carrying capacity scatter is obtained, very little increase in gear tooth scuff is obtained at lubricant flow rates down to 100 ml/min. Test oil flow rate studies were also made at conditions of higher initial average percent scuff as shown in Figure 22. It was thought that at the higher loads necessary to produce 22 to 25 percent average scuff, the break in the scuff versus flow rate curve might occur at a flow rate above 500 ml/min. As can be seen, for those lubricants with which a large increase in scuff was obtained, the increase occured at lubricant flow rates below 500 ml/min.

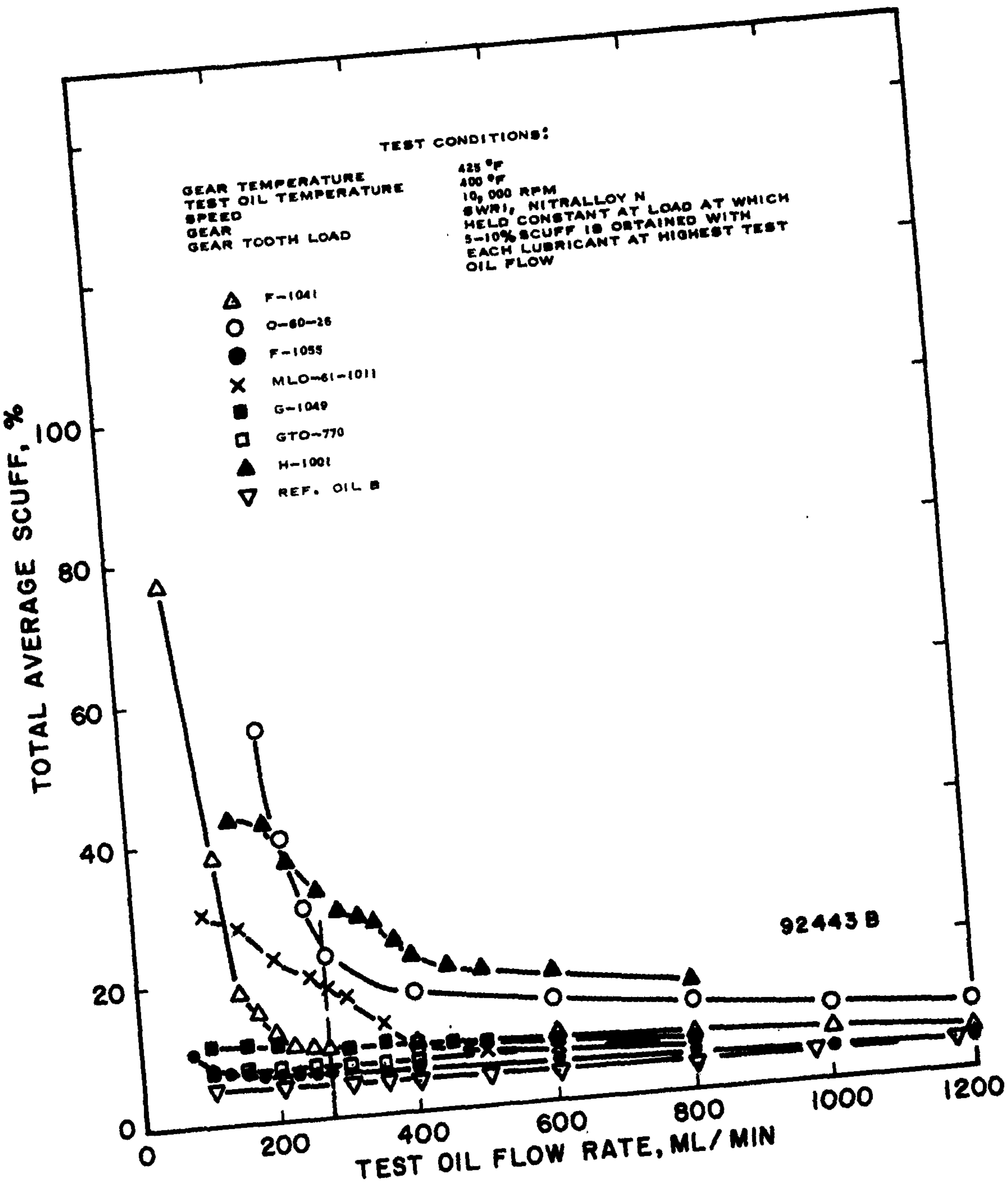

FIGURE 20. EFFECT OF LUBRICANT FLOW RATE ON GEAR TOOTH SCUFFING AT 425°F TEST GEAR TEMPERATURE CONDITIONS

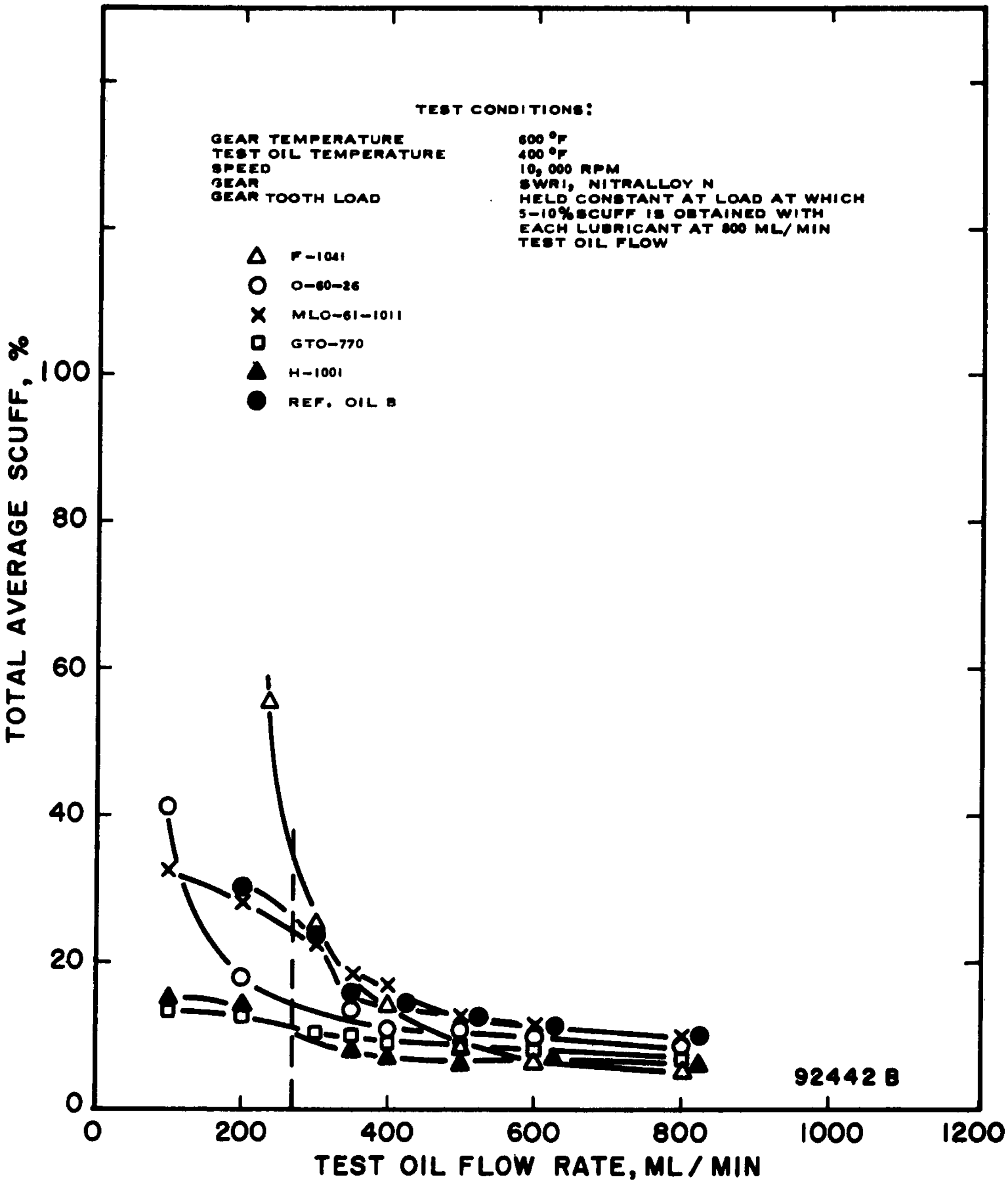

FIGURE 21. EFFECT OF LUBRICANT FLOW RATE ON GEAR TOOTH SCUFFING AT 600°F TEST GEAR TEMPERATURE CONDITIONS

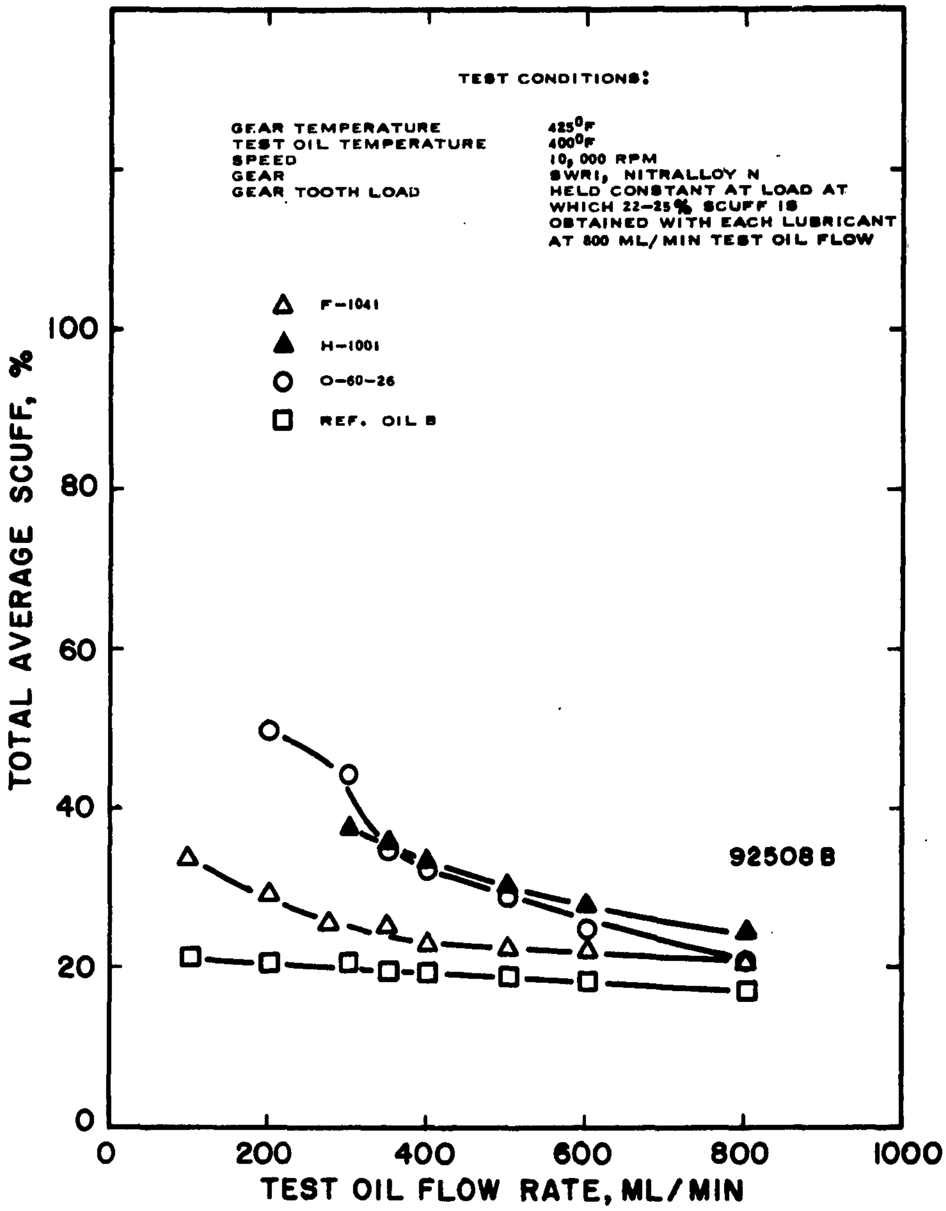

FIGURE 22. EFFECT OF LUBRICANT FLOW RATE ON GEAR TOOTH SCUFFING AT 425°F TEST GEAR TEMPERATURE CONDITIONS

A plot of average percent scuff increase obtained between 800 and 270 ml/min test oil flow rates versus the percent standard deviation/ mean load-carrying capacity obtained in load-carrying capacity determinations with the same lubricants is shown in Figure 23. It can be seen that generally the greater the scuff increase obtained, the greater the load-carrying capacity scatter. A statistical analysis of the 425°F data shown in Figure 23 gives a correlation coefficient of 0.85. The correlation coefficient for the 600°F data was determined as 0.48. It is not expected that additional data will improve the 600°F relationship since it is believed that the lubrication mechanism at 600°F differs from that at 425°F and may not be as readily affected by lubricant flow rate.

Load-carrying capacity determinations were made on two lubricants at 425°F test conditions with a lubricant flow rate of 500 ml/min to determine the effect of increased test oil flow rate on load-carrying capacity. A comparison of the results obtained using 500 and 270 ml/min test oil flow rate is shown in the following tabulation:

Oil Code	Test Oil Flow, ml/min	Load-Carrying Capacity, lb/in.	Std, Dev., lb/in.	Std. Dev. ÷ Mean, %
F-1041	270	1040 (6)	128	12.3
	500	1850 (4)	99	5.4
H-1001	270	740 (4)	238	32.3
	500	1030 (6)	203	19.7

A significant increase in load-carrying capacity was obtained for both lubricants when test oil flow was increased to 500 ml/minute. In addition, the 500 ml/min test oil flow rate decreased the ratio of standard deviation to the mean load-carrying capacity by 56 percent for F-1041 and 39 percent for H-1001.

It is not intended to predict that load-carrying capacity scatter will be eliminated by merely increasing the test oil flow rate, for there are other factors such as gear geometry, gear tooth surface finish, gear tooth hardness, etc., which also affect load-carrying capacity scatter. However, it is felt that at flow rates of 500 ml/min or above, load-carrying capacity scatter could be somewhat reduced.

E. Calibration of the WADD High-Temperature Gear Machine

Calibration data for the WADD high-temperature gear machine had previously been reported[1] for speeds up to 10,000 rpm and test gear temperatures up to 700°F. During this reporting period, dynamic calibration of the

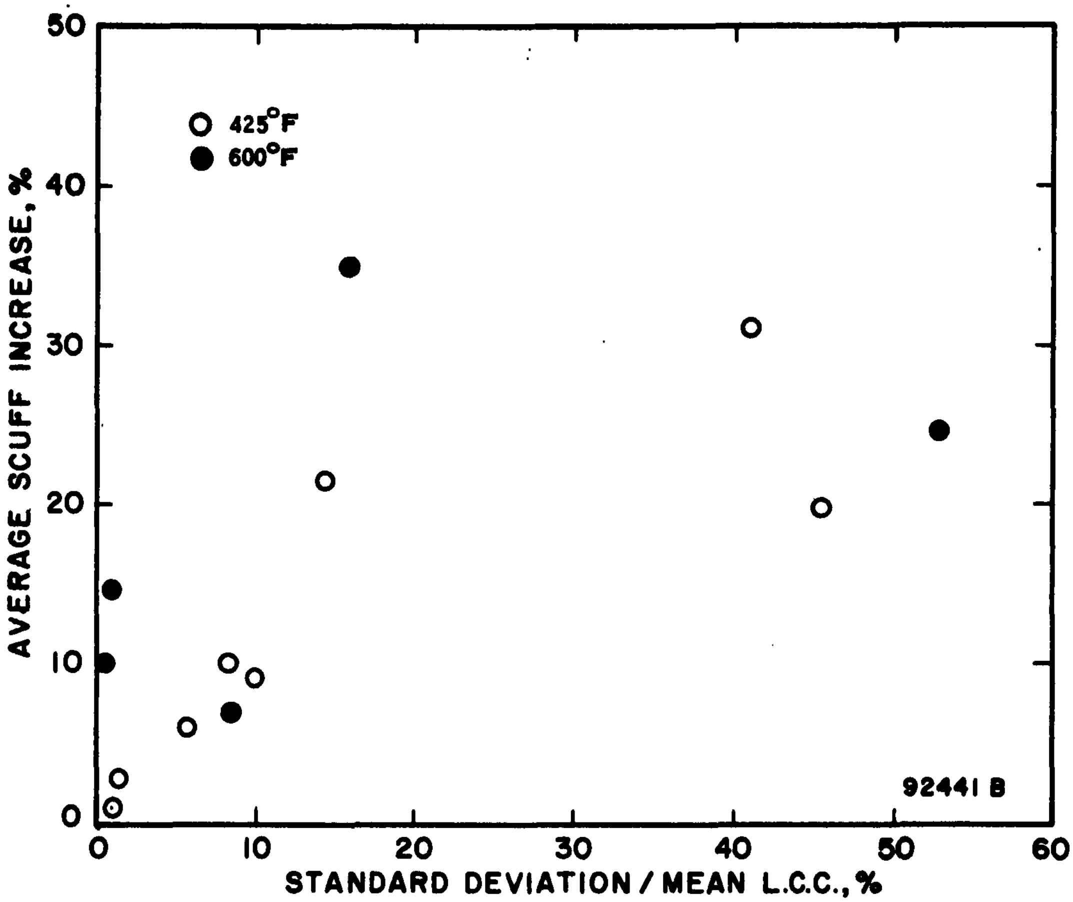

FIGURE 23. RELATIONSHIP BETWEEN AVERAGE SCUFF INCREASE OBTAINED BETWEEN 800 AND 270 ML/MIN TEST OIL FLOW RATE AND LOAD-CARRYING CAPACITY SCATTER OBTAINED WITH THE RESPECTIVE LUBRICANTS

machine was extended to include 15,000 and 20,000 rpm at 165°F test conditions. To accomplish this high-speed calibration, it was necessary to increase the support roller bearing clearance from 0.0025 to 0.006 in. The air seal and load seal clearances were increased accordingly. The slip-ring assembly was reworked to replace worn parts and was modified for high-temperature operation by providing oil cooling to the outer-rings.

The results obtained are shown in Figure 24. It will be noted that a 10,000 rpm calibration curve was obtained, using the larger bearing clearances, for reference. The correlation between the static and dynamic curves is approximately the same at 15,000 and 20,000 rpm as was obtained earlier at the lower speeds. The 20,000 rpm calibration run was limited to only the 10, 20, 40 and 60 psi load pressure in order to reduce the operating time of the slip-ring assembly at this speed.

An attempt was made to calibrate the machine at 30,000 rpm. However, the mercury temperature could not be maintained so as to prevent vaporization of the mercury in the ringcells. At these conditions, the irregularity of the strain measurement through the slip-ring assembly was such that strain readings could not be obtained.

F. Conclusions

The load-carrying capacity of the lubricants evaluated shows that as the test gear temperature was increased from 165 to 400°F, the load-carrying capacity decreased as much as 50 percent with some lubricants. In the 400 to 500°F temperature region, the load-carrying capacity of each lubricant reached a minimum value, beyond which an additional increase in test gear temperature resulted in an increase in load-carrying capacity for each lubricant.

Even though it appears that a general nonlinear relationship of 165 and 425°F load-carrying capacity results, using Nitralloy N steel test gears, may exist over the load-carrying capacity range of the lubricants included in this program, the relationship is not sufficiently definitive in the range of normal interest to allow extrapolation of 165°F load-carrying capacity data to predict accurately the results which might be expected at 425°F.

It was demonstrated that the volume of the test oil system, within the limits included in this investigation, has an effect on the load-carrying capacity determination at 600°F. It appears that the lubricant decomposition products existing both as deposits on the test gears and as a suspension in the test oil bulk, have an effect on load-carrying capacity at gear temperatures above 425°F. The results obtained indicate that varied behavior with respect to load-carrying capacity can be expected when different lubricant types are evaluated at temperatures above 425°F.

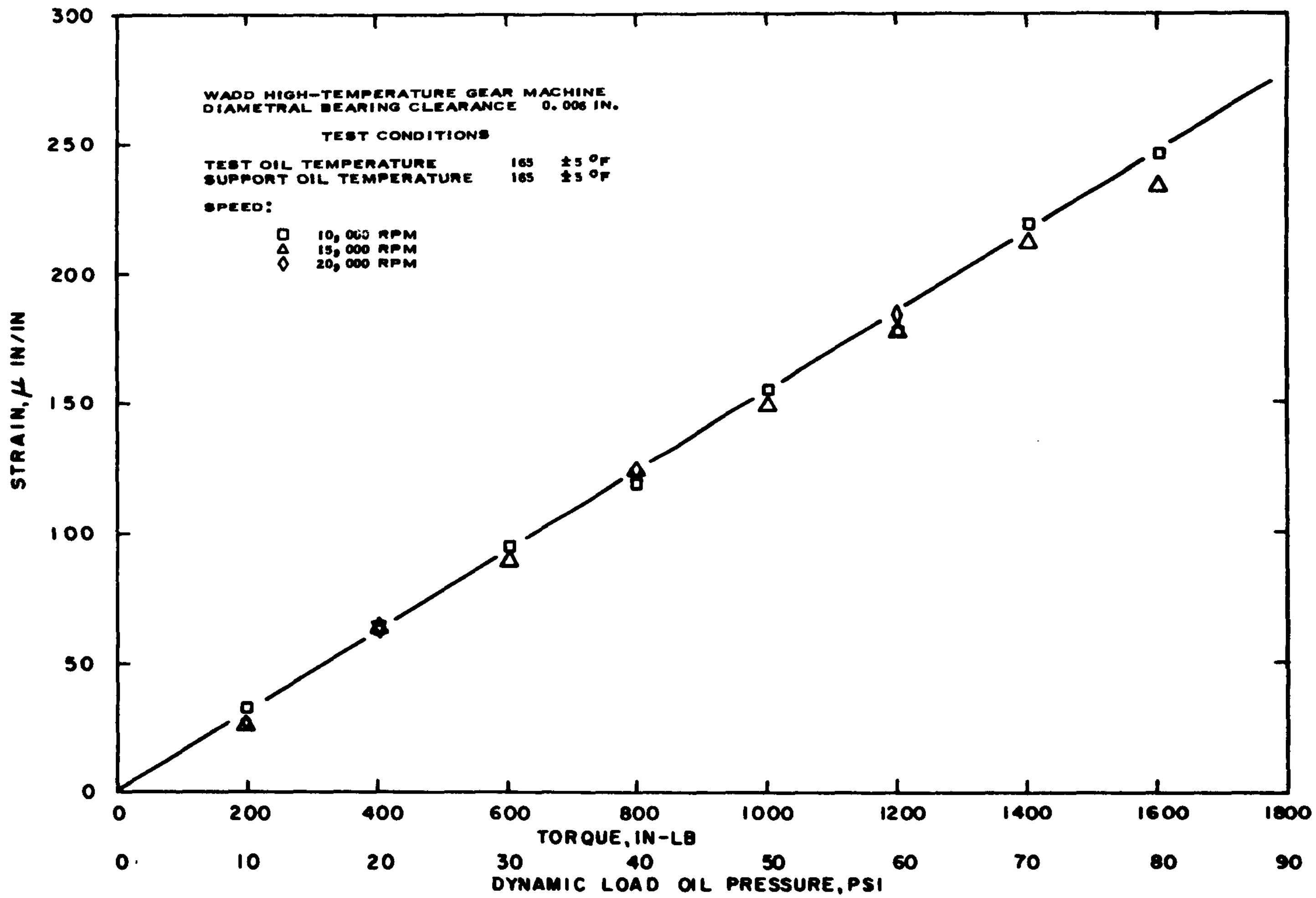

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FIGURE 24. COMPARISON OF STATIC AND DYNAMIC CURVES FOR HIGH SPEED CALIBRATION

The effect of test oil flow rate was shown to have an effect on gear tooth scuffing with most lubricants and that load-carrying capacity could be deleteriously affected at test oil flow rates below 500 ml/min in gear tests with those lubricants.

The WADD high-temperature gear machine load constant of 11.5 was investigated and found to be valid at 165°F test conditions and test gear speeds through 20,000 rpm. However, it was necessary to increase the clearance in the support roller bearings of the machine to 0.006 in. for this investigation.

V. ROLLING-CONTACT FATIGUE

A. General Remarks

The objectives of the rolling-contact fatigue phase of the program were to develop apparatus and procedures for evaluating lubricants with respect to rolling-contact fatigue and to evaluate candidate lubricants under environmental conditions representative of Mach 2.5 to 3 class gas turbine engine designs.

Rolling-contact fatigue is a critical problem in extended engine operation, and there is evidence that lubricants exert a strong influence on rolling-contact fatigue. In the program covered by this report, it was planned to evaluate lubricants with respect to rolling-contact fatigue in two ways. First, by using a bench-type apparatus, the 3-ball/cone fatigue tester, which was designed and fabricated under this contract. After initial screening tests in the 3-ball/cone fatigue tester, the more promising lubricants were to be evaluated in 85-mm full-scale ball bearing test machines. However, the unexpected long time required for fabrication of the final design of the 3-ball/cone fatigue tester and the acquisitions of test specimens enabled only a preliminary test program to be conducted using the 3-ball/cone fatigue tester. Therefore, no fatigue testing was initiated using the 85-mm full-scale bearing test machines.

The 3-ball/cone fatigue tester[1] was developed to provide a reasonably simple bench-type device capable of evaluating lubricants and studying the effect of operating variables prior to full bearing rolling-contact fatigue studies.

In first attempts to apply a static load on the balls, some difficulty was experienced in the movement of the sleeve bearing assembly. On disassembly, it was found that extensive galling of the sleeve bearing had occurred. The sleeve bearing surfaces were then undercut and electroplated with approximately 0.015 in. of hard chromium. The bearing surfaces were then reground and the sleeve bearing reinstalled; thereby eliminating the galling problem.

Initial operation of the fatigue tester at test conditions of 165°F test oil-in and ball/cone temperature, 10,000 rpm, and light loads, the sleeve bearing containing the spindle support bearings showed evidence of seizure in the sleeve bearing liner. It was found that this seizure was caused by thermal expansion of the sleeve bearing due to heat transferred from the spindle support bearings. An increase in diametral clearance between the sleeve bearing and sleeve bearing liner eliminated this difficulty. The diametral

clearance between the spindle support bearings and support bearing housing was also increased slightly in view of the higher than expected operating temperature of the spindle support bearings.

With the additional clearance described above, the 3-ball/cone fatigue tester was operated at test oil-in temperatures up to 500°F and ball/cone temperatures up to 600°F. Satisfactory performance was obtained with respect to temperature, speed, and load control.

Preliminary fatigue testing was initiated using a prototype M-50 steel cone specimen for the purpose of determining the operating capabilities of the tester and to study the mode of any fatigue failures obtained. The conditions of the preliminary tests were 450°F test oil-in temperature, 50 ml/min test oil flow rate, 500°F ball/cone ambient temperature, load to give a maximum Hertz stress of 757,000 psi, and 10,000 rpm cone speed.

During the preliminary testing with lubricants of two different types, it was found that considerable sludge formed in the test section and in the test oil system. It was felt that the test oil flow rate used in these tests was possibly so low that the residence time of the test oil in the test section induced excessive sludge formation. By increasing the test oil flow rate to 200 ml/min in a subsequent test, the sludge formation was effectively reduced.

After demonstrating the capabilities of the tester with regard to high-temperature operation, preliminary fatigue testing was continued at less severe temperature conditions for the purpose of obtaining operating time and experience on the tester and to study the mode of any failures obtained. Prototype M-50 steel cone specimens, made from a supply of M-50 steel available at SwRI, were used in the program. Test conditions were set at 200°F test oil-in and test specimen temperature, 200 ml/min test oil flow rate, 10,000 rpm cone speed, and load to give a maximum Hertz stress of 600,000 psi. Seven fatigue tests were made with the prototype specimens, and a smooth Weibull plot of the resulting data was obtained. In continuing the preliminary testing program, 50 additional sets of test specimens were procured. The cone specimens were made from another supply of M-50 steel on hand at SwRI, which was a reserve of the material used in the manufacture of 85-mm thrust bearings for use in later full-scale bearing fatigue testing. The results obtained in fatigue testing with these cone specimens varied widely from the results obtained with the specimens used in the earlier seven tests noted above. Efforts were made to determine the reason or reasons for the wide variation in results obtained using the cone specimens from the two different batches of steel. The problem was discussed with the steel supplier and the manufacturer of the specimens and no conclusive answer could be reached.

The torque measurement system of the tester was dynamically calibrated at loads to give up to 9×10^5 psi maximum Hertz stress. Excellent

performance was obtained from the torque measurement system during preliminary testing. Fatigue of the cone specimen was experienced in several of the preliminary fatigue tests. In each case, the measured and recorded torque indicated failure simultaneously with audible indications.

The operation and performance of the tester continues to be satisfactory. To date the tester has accumulated a total of over 500 hours of operation.

B. Apparatus and Techniques

The basis of selection, design requirements, and description of design features of the 3-ball/cone fatigue tester have been previously reported.[1]. With the exception of various minor clearance changes, no changes in design, operating principle, or instrumentation have been made.

A brief description of the components used to make up the 3-ball/cone fatigue tester is presented in the following paragraphs. For the sake of clarity, the tester is divided into four basic sections--the drive section, the support section, the test section, and the test oil section. The components of each section are shown in Figure 25 with exception of the complete drive section.

1. Drive Section

The drive section consists of the drive motor, drive motor control, drive belt, (not shown in Fig. 25), dual bearing supported drive shaft, R, and drive shaft housing. The drive shaft housing is mounted on the support framework. Mounted in the drive shaft housing are the magnetic pickups for the revolution counter and the speed indicator.

2. Support Section

The support section consists of the spindle, F, slip-ring assembly, T, spindle support bearings and support bearing spacers, W, support bearing housing, X, sleeve bearing, Y, and sleeve bearing liner, Z. The sleeve bearing liner is by weldment an integral part of the support framework. The load system is included in the support section. The load system consists simply of the load ring, M, load arm, weight hanger and weights.

3. Test Section

The test section supports the specimens (the balls, cylinder, G, and washer, H) and consists of the test body, D, cylinder retainer, body support, V, and air thrust bearing, N.

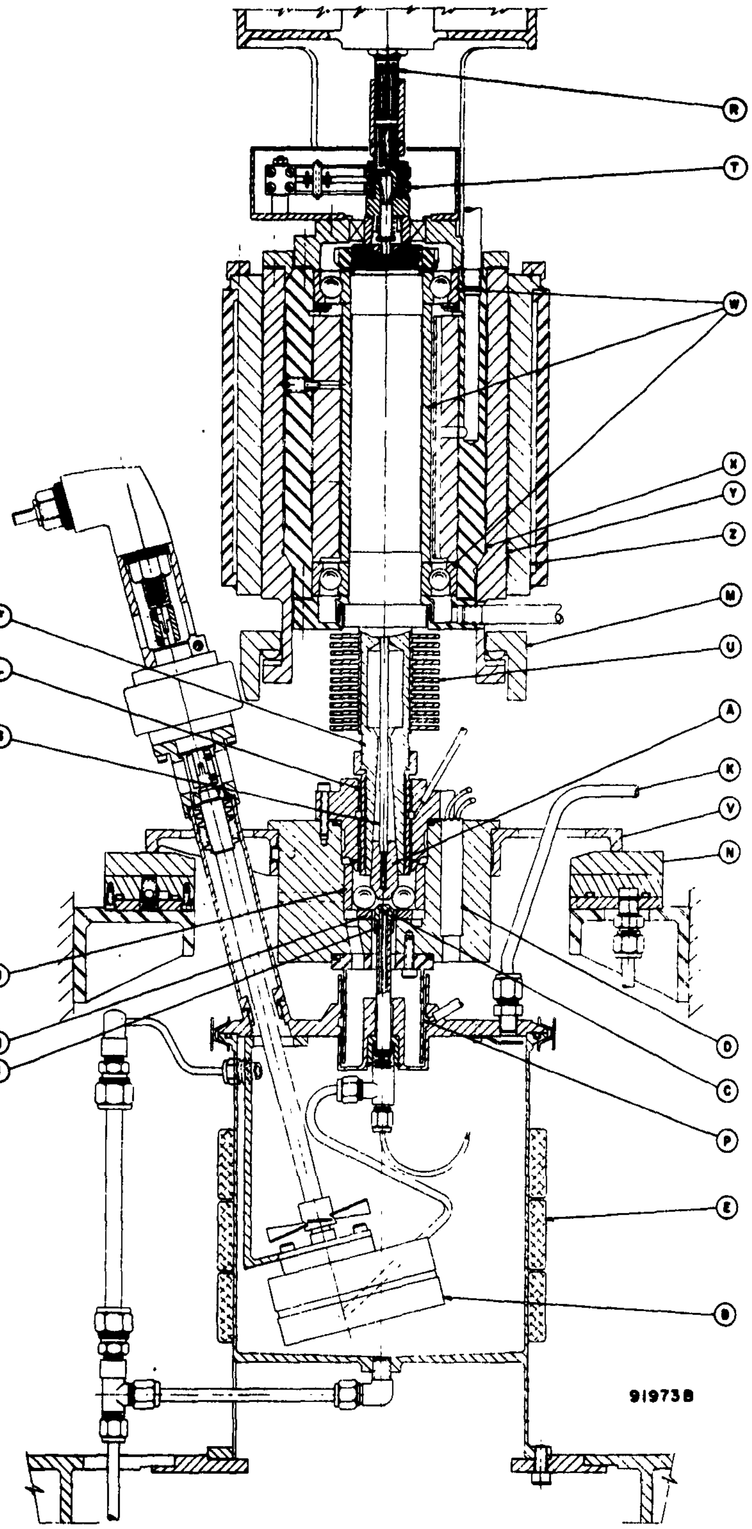

FIGURE 25. CROSS SECTION OF THREE-BALL/CONE FATIGUE TESTER

4. Test Oil Section

The test oil section consists of the test oil sump, E, test oil pump, B, test oil jet, J, and the test oil pump drive motor.

5. Instrumentation

Instrumentation consists of (a) drive speed control, (b) spindle speed indicator, (c) spindle revolution counter, (d) measurement and recording of cone specimen, cylinder specimen, test oil-in and test oil sump temperatures, (e) test body and test oil temperature controllers, (f) test oil pressure failure control, and (g) strain gage torque measurement indicator and recorder.

The drive speed control is obtained by a variable-speed DC motor control. The speed is controlled to ± 50 rpm at the operating spindle speed of 10,000 rpm. The speed is measured by an electronic speed indicator which is triggered by a magnetic pickup. Revolutions or operating cycles are indicated by an electronic time interval meter which is also triggered by the magnetic pickup. The cone and cylinder specimens, test oil-in, and test oil bulk temperatures are recorded by a multipoint temperature recorder. Control of cylinder specimen and test oil-in temperature is obtained by on-off heater controllers. Powerstats are used in the heater lines to prevent overheating of the heaters and to give smooth heat control. Test oil pressure is indicated by a pressure gage. Should failure of test oil pressure occur, the tester is shut down by a pressure-sensitive switch.

The torque measurement system consists of two strain-gage instrumented, flexible lever, restraining arms attached to the support framework. The lever arms are located 180° apart. Each lever arm is contacted by a pin located in the test body support which is supported by the air thrust bearing. The strain gage system is a dual full-bridge system, with a full-bridge system on each of the two lever arms. The output of the strain gages is indicated on a strain gage indicator. The output of the strain gage indicator is in turn recorded by a milliampere recorder. The recorder is instrumented such that should the measured torque exceed a predetermined and preset value, due to an increase in friction between the rotating cone and balls, all systems of the fatigue tester are shut down automatically with the exception of the revolution counter.

With these systems of control, the fatigue tester, once control has been established, is fully automatic and can be left unattended during a test.

Considerable difficulty was experienced in preliminary tests with the cage used to separate and space the test balls. In the early considerations of cage type, it was decided that a ball-riding cage was the most suitable type for this work. It was noted that after one or two hours of operation, vibration in the test section tended to increase. Upon inspection of the cage at the termination of several hours of operation, extreme wear of the cage was found. Indications were that the cage was contacting the cone specimen at the upper edge of the inside diameter of the cage. Utilizing a high-speed drill press, with the cylinder and washer specimens held in a drill press vise and the cone held in the drill press chuck, the action of the cage was observed with the aid of a stroboscope. It was found that the cage would ride up the test balls, and gyrate around and contact the cone specimen. This action was observed to be very similar to that of a "hula hoop." The force of the cage-cone contact was sufficient to cause considerable wear on the upper inside diameter of the cage. Several modifications of the cage and cage redesigns did not result in any significant improvement in cage operation. It was decided that some other means of spacing the three test balls was needed. It was found that a 13/32 in. diameter ball would fit with a clearance of 0.010 in. in the space between the 1/2 in. diameter test balls when the latter are in their normal operating position. In this manner the test balls are maintained in their respective positions and the smaller spacer balls do not contact the cone specimen. Also, the spacer balls are held in position by centrifugal force and do not tend to ride up the test balls. In subsequent fatigue test operations using this method, practically all vibration previously experienced in the test section was eliminated. Also, the fatigue data obtained using the spacer balls and the ball-riding cage fall on the same Weibull line. However, as will be seen, the data points obtained using the spacer balls are closely grouped near the middle of the Weibull line.

C. Calibration of the Torque Measurement System

Torque produced by friction between the rotating cone and the balls is indicated by the force applied to the flexural restraining arms causing a change in the current flow through the strain gages attached to the restraining arms. This change in current flow is indicated by the strain gage indicator as a change in strain in μ in./in. A curve produced by a plot of a known torque versus the output of the strain gages provides a means of determining an unknown torque produced during dynamic operation. Since the application of a known torque is best made under static conditions, the curve produced is referred to as a static calibration curve.

The static calibration was accomplished by hanging weights from a string over a small ball bearing pulley with the free end of the string attached to a pin which contacts one of the restraining arms. With the cone lightly lubricated, a slight load was applied to the balls by the cone specimen so as

to prevent lateral movement of the air thrust bearing. By varying the weights hanging from the string, strain gage measurements were made at various torque levels of from zero to 36 in.-oz. A plot of these data is shown in Figure 26.

Dynamic calibration at conditions of 400°F test oil-in and 500°F ball/cone ambient was next obtained by step-loading the cone on the balls at load levels to give maximum Hertz stresses from 400,000 to 900,000 psi. The calculated maximum Hertz stress produced by the load was obtained from the stress versus load curve shown in Figure 27. With the strain gage data obtained, the torque was determined from the curve of Figure 26. With these data, then, the dynamic calibration curve shown in Figure 28 was obtained. It is pointed out that because of the viscosity characteristics of the test lubricant, the dynamic calibration curve shown is valid only for this one lubricant within reasonable temperature limits.

D. Preliminary Operation

In the first attempts to operate the tester at a light load, the intended operating speed of 10,000 rpm, and at 165°F ball/cone ambient, the sleeve bearing seized in the sleeve bearing liner within a few minutes after operational speed was obtained. The seizure was determined to be due to thermal expansion of the sleeve bearing from heat generated by the spindle support bearings. It is evident that an excess of clearance between the sleeve bearing and sleeve bearing liner could introduce misalignment of the spindle. The clearances mentioned in the following paragraph may appear to be excessive for precision alignment of the drive spindle. However, these clearances were measured at room temperature and, therefore, are larger than those that would be measured at operating temperatures. In order to insure against any possible misalignment or cocking of the spindle, two spring-loaded Teflon wedges were incorporated into the design in such a way that the sleeve bearing is lightly held against the sleeve bearing liner.

The clearance between the spindle support bearings and the support bearing housing was increased to 0.0015 in., to allow for thermal expansion of the spindle support bearings. After increasing this clearance, the diametral sleeve bearing clearance was increased in increments of 0.001 in. until the required clearance was obtained. At a clearance of 0.002 in., the sleeve bearing moved freely for about 40 minutes of operation before the sleeve bearing seized. An attempt was then made to increase the clearance by an additional 0.0005 inch. The resultant additional increase was 0.0007 inch. At this diametral sleeve bearing clearance of 0.0027 in., the tester was operated for a period of several hours and the axial movement of the sleeve bearing remained free.

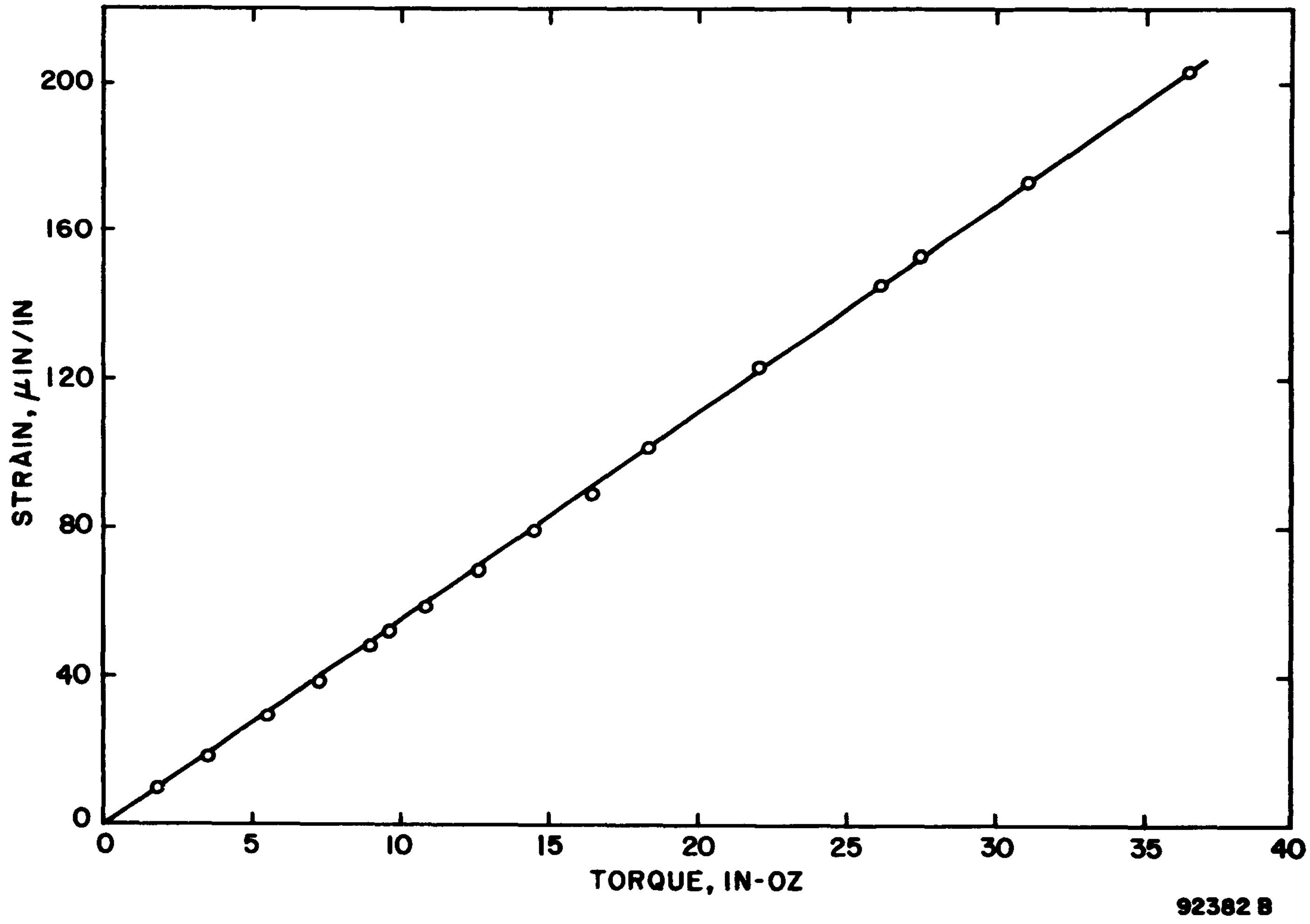

FIGURE 26. STATIC CALIBRATION OF STRAIN GAGE TORQUE MEASUREMENT SYSTEM OF 3-BALL/CONE FATIGUE TESTER

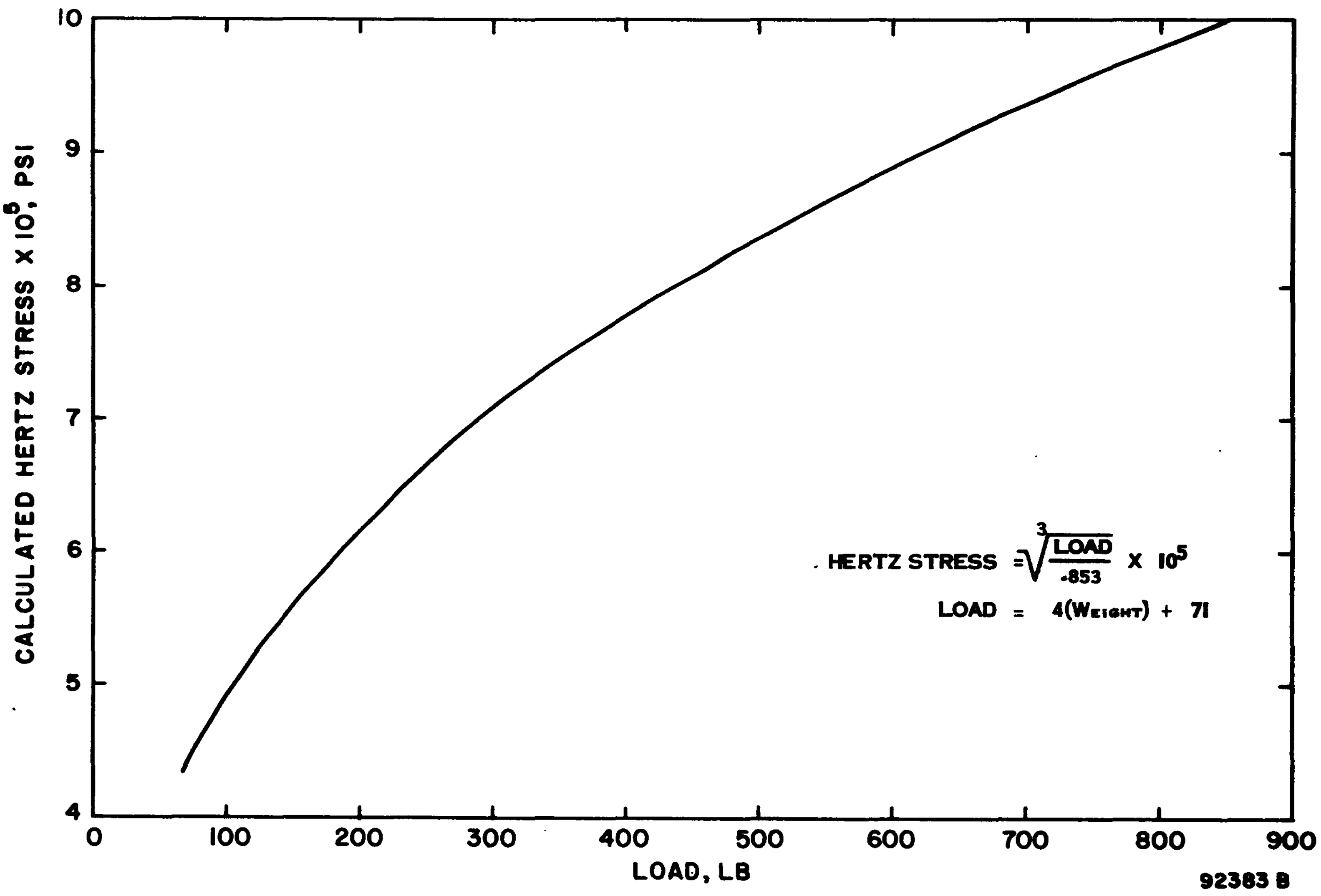

FIGURE 27. LOAD VERSUS CALCULATED HERTZ STRESS FOR 3-BALL/CONE FATIGUE TESTER

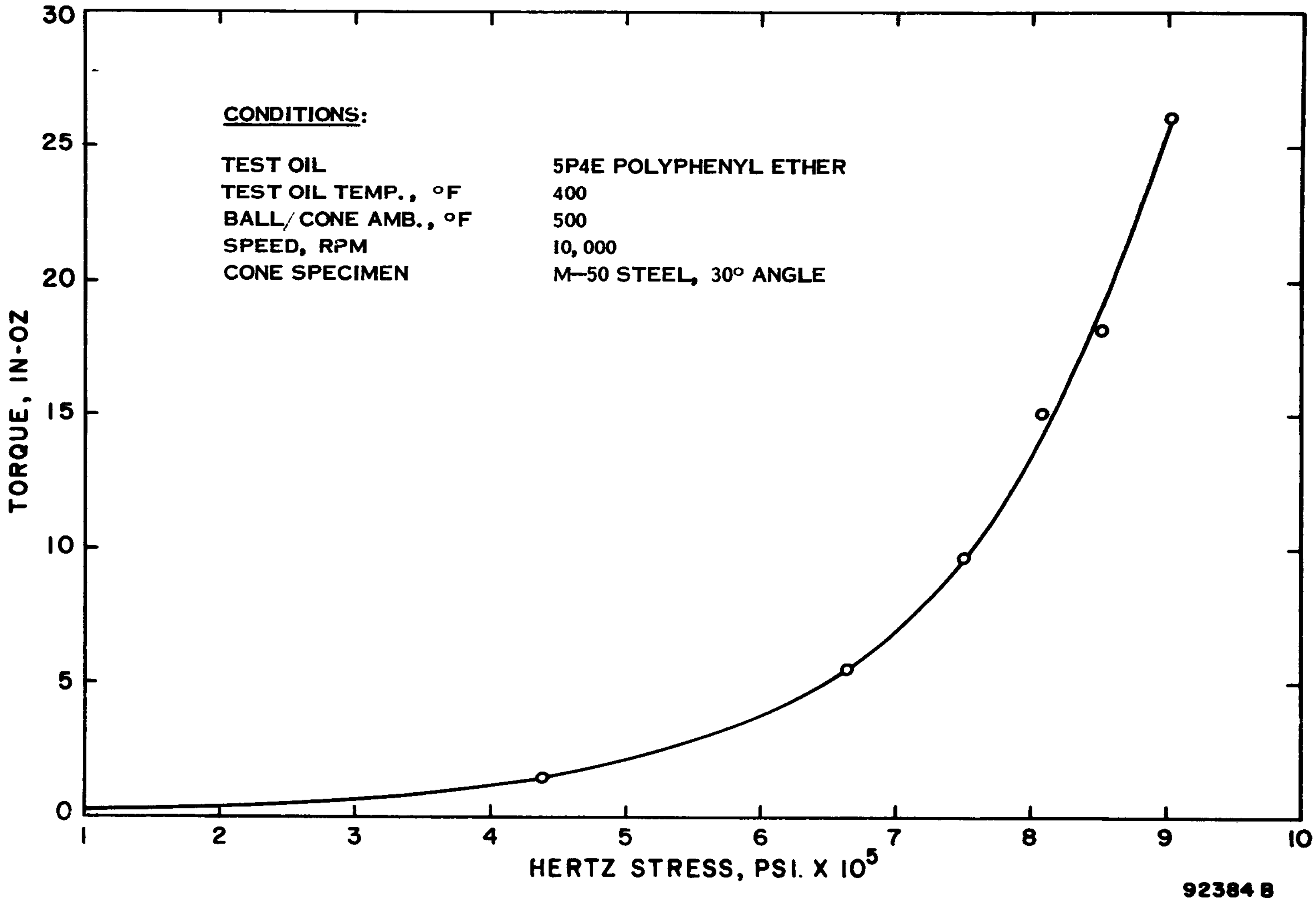

FIGURE 28. DYNAMIC CALIBRATION OF STRAIN GAGE TORQUE MEASUREMENT SYSTEM OF 3-BALL/CONE FATIGUE TESTER

To determine the effect of test section temperature on the operation of the tester, the tester was operated at conditions of 400°F test oil-in, 400°F ball/cone ambient, 10,000 rpm, and a load to give approximately 100,000 psi maximum Hertz stress, for a period of 5 hr without difficulty. Since the operating performance was satisfactory at these conditions, the ball/cone ambient temperature was increased to 600°F. The fatigue tester operated satisfactorily for a period of 6 hr again without difficulty. At this point, it was decided to determine the effect of load on the operational performance of the tester. The tester was operated at a load to give a maximum Hertz stress of 436,000 psi, 400°F test oil-in, and 600°F ball/cone ambient. Satisfactory performance was obtained for a period of 10 hr. At this point, the load was increased to give a maximum Hertz stress of 700,000 psi. Satisfactory performance was obtained for a period of about 5 minutes whereupon a failure of the cone was noted both audibly and simultaneously by an increase in the measured torque. The torque limiting setting of the torque recorder was set at full scale so that the effect of progressive cone failure on torque could be observed. The degree of failure continued to increase gradually, as evidenced by an increase in audio level and measured torque, for a period of two minutes whereupon a large increase in torque was suddenly obtained causing the torque indication to go full scale and the torque limiting controller to shut down the tester. On disassembly of the test section, the cone was found to be severly pitted over about one-third of the contact surface. The behavior of the torque measurement system indicates that the occurence of spalling during fatigue testing may be detected very nearly the instant of its occurrence.

The test lubricant used in these preliminary operations was Grade 1065 mineral oil.

E. Preliminary Fatigue Testing

Preliminary fatigue testing was initiated using Prototype M-50 steel cone specimens for the purpose of exploring the operating capabilities of the tester and to study the mode of any fatigue failures obtained. The conditions of the test were 450°F test oil-in temperature, 500°F ball/cone ambient temperature, load (75 lb weight--371 lb load on the cone) to give a maximum Hertz stress of 757,000 psi, speed of 10,000 rpm,with 5P4E polyphenyl ether as the lubricant. The test oil flow rate was 50 ml/min. When the load was applied at operating speed and test temperature, the measured torque of 9.75 in.-oz agreed exactly with the dynamic calibration curve shown in Figure 28. During the test the torque level remained constant and steady for a period of 17 hr. At this time, the tester was shut down for the purpose of inspecting the cone. No spalling or pitting was noted. However, a smooth and unexpectedly wide and deep wear track was noted. The width and depth of the wear

track were measured at 0.097 and 0.0028 in., respectively. It was decided to continue the test to determine if additional wear or fatigue failure would be obtained. When attempts to resume the test were made, no test oil flow could be obtained. It was found that the test oil pump, test oil pump bracket, test oil lines, test oil pump inlet filter screen and the bottom of the test oil sump was covered with a heavy sludge to a depth of about 0.250 in. A viscosity determination of a sample of the oil drained from the sump gave a viscosity of 320.8 cs, which is 33.7 cs below that of the new oil. A similar sludge condition in a test oil sump has never been experienced previously with the 5P4E polyphenyl ether in any of the various phases of the program, even at more strenuous temperature conditions. The possibility of contamination of the test oil before and/or during the test was investigated and no evidence of contamination was found. It is thought that possibly the low test oil flow rate (50 ml/min) could be a factor in the gross sludging of the test oil since, with gravity drain, the test oil circulation time through the test section is much greater than in the bearing deposit or gear test machines. Also, with the nearness of the spindle air seal to the ball/cone region, a considerable amount of air passes through this region. It was thought that if the test oil flow rate was increased to 200 ml/min, the residence time of the test oil in the test region would be reduced, and, since the pump shaft will turn at a higher speed, the impeller mounted on the pump shaft would keep the bulk oil agitated to a greater extent.

With the above in mind, the test oil system and test section were thoroughly cleaned and a new charge of oil was put in the test oil sump. New balls with cylinder and washer specimens that had been used, but had little wear, were installed. The cone used in the test described above was installed since no new cone specimens were available. With a test oil flow rate of 200 ml/min, the test was then resumed under the test conditions described earlier. After a period of 17 hours the test was terminated and the test section, test oil sump, and test specimens examined. Some sludging was obtained. However, the extent of sludging was considerably less than before. The wear track in the cone specimen was found to be 0.140 in. wide and 0.012 in. deep, a considerable increase over the 0.097 in. width and 0.0028 in. depth obtained in the first test.

Since the high temperature and high load capabilities of the tester have been demonstrated, it was decided to carry out the additional preliminary testing at less severe test temperature conditions in order to eliminate the additional time required in high-temperature operation to disassemble and clean the tester after each test.

The results obtained in preliminary fatigue tests where operating conditions were set and controlled for the purpose of obtaining fatigue of the cone specimen are presented in Table 55. The conditions of the tests are as

TABLE 55. RESULTS OF PRELIMINARY 3-BALL/CONE FATIGUE TESTS

Test No.	Test Oil	Test Time, hours	Fatigue Point	Remarks
1	F-1055	15.6	Cone	Performance satisfactory
2	F-1055	10.4	Cone	Performance satisfactory
3	F-1055	8.8	Cone	Performance satisfactory
4	F-1055	18.9	Cone	Performance satisfactory
5	F-1055	16.6	Cone	Performance satisfactory
6	F-1055	13.7	Cone	Performance satisfactory
7	F-1055	15.0	Cone	Performance satisfactory
8	F-1055	12.3	Test ball (2)	First test with cone from different material supply
9	F-1055	7.3	Test ball (1)	
10	F-1055	72.9	None	
11	F-1055	3.5	Test ball (3)	
12	F-1055	3.5	Test ball (1)	
13	F-1055	181.2	None	Increased load to produce maximum
14	GTO-880	1.6	Test ball (2)	Hertz stress of 700,000 psi after 32 hr and 800,000 psi after 65 hr
15	GTO-880	122.9	Test ball (2)	Failure between test ball and washer specimen
16	GTO-880	1.6	Test ball (2)	
17	GTO-880	46.8	Test ball (3)	Failure between test ball and washer specimen

Test oil temp, °F	200
Test oil flow, ml/min	200
Test specimen temp, °F	200
Speed, rpm	10,000
Load, lb	191
Maximum Hertz stress, psi	600,000
Cone contact angle, degrees	30

All specimens and test balls made from M-50 vacuum remelt steel.

follows: 200°F test oil, 200°F ball/cone specimen temperature; 10,000 rpm cone speed; load (191 lb) to give a maximum Hertz stress of 600,000 psi with the 30° cone specimen.

It will be noted that successful fatigue of the cone specimen was obtained in the first seven tests. At this point the supply of prototype specimens manufactured at SwRI was exhausted and additional specimens were procured. The new cone specimens were made of M-50 steel (ball wire) on hand at SwRI. This steel was obtained from the same melt as that used in the manufacture of the 85-mm thrust bearings for use in the full-scale bearing fatigue program. The cylinder and washer specimens were made of the same material as that used in the first specimen order, i.e., Latrobe Steel Company designation MV-1 high-speed tool steel reported by this company as consumable electrode-vacuum remelted M-50 steel. As can be seen in Tests 8 through 17, no fatigue failures of the cone specimen were obtained. In these tests with the new cone specimens, fatigue failures were experienced in one or more of the three test balls except in Tests 10 and 13 where no failure was obtained during approximately 73 and 181 hours of operation, respectively, before the tests were terminated. In an effort to obtain cone failure in test 13, the maximum Hertz stress was increased to 700,000 psi after 32 hours of operation, and at 65 hours the maximum Hertz stress was increased to 800,000 psi. The test continued at this stress level for an additional 116 hours before being terminated. No evidence of pitting was found on any of the test specimens or slave balls.

At this point it was decided to change to a lubricant of lower bearing fatigue life [3]. GTO-880, a diester sebacate was selected. Tests 14 through 17 were made at 700,000 psi maximum Hertz stress using GTO-880 as the lubricant. As can be seen, failures were obtained on the test balls rather than on the cone specimen.

Though there is no supporting evidence, it appears as though the quality of the steel used in the second batch of cone specimens is superior to that used in the first batch. Also the results tend to show that the steel quality of the ball specimens is superior to the quality of the steel used in the first batch of cone specimens and is considerably inferior to the steel used in the second batch of cone specimens.

The manufacturer of the ball specimens was contacted in this regard and it was agreed that a different batch of ball specimens should be used. The new batch of balls were received but additional testing could not be initiated before this writing.

A Weibull plot of the fatigue data obtained in Tests 1 through 7 is shown in Figure 29. As can be seen, a very reliable curve may be obtained from the points plotted. The smoothness of the curve was surprising and unexpected in view of the fact that some of the cone and cylinder specimens had as much as 0.0003 in. run-out and out-of-roundness, respectively. As pointed out earlier, in view of the relatively poor precision of these specimens, no significance has been attached to the fatigue life obtained. It is difficult to determine if the fatigue failures obtained in these tests were due to load bearing failure of the material-lubricant combination or due to the poor precision of the specimens used. Obviously, this can only be determined by fatigue tests with higher precision specimens.

F. Conclusions

Continued experience has been obtained in the operation of the 3-ball/cone fatigue tester, and the performance of the tester has continued to be satisfactory.

From these preliminary operations, it may be concluded that test section temperatures up to 600°F and maximum Hertz stress up to 700,000 psi have little or no effect on the performance of the support section.

It has been demonstrated that imperceptible changes in the cone specimen material may produce widely varied fatigue results.

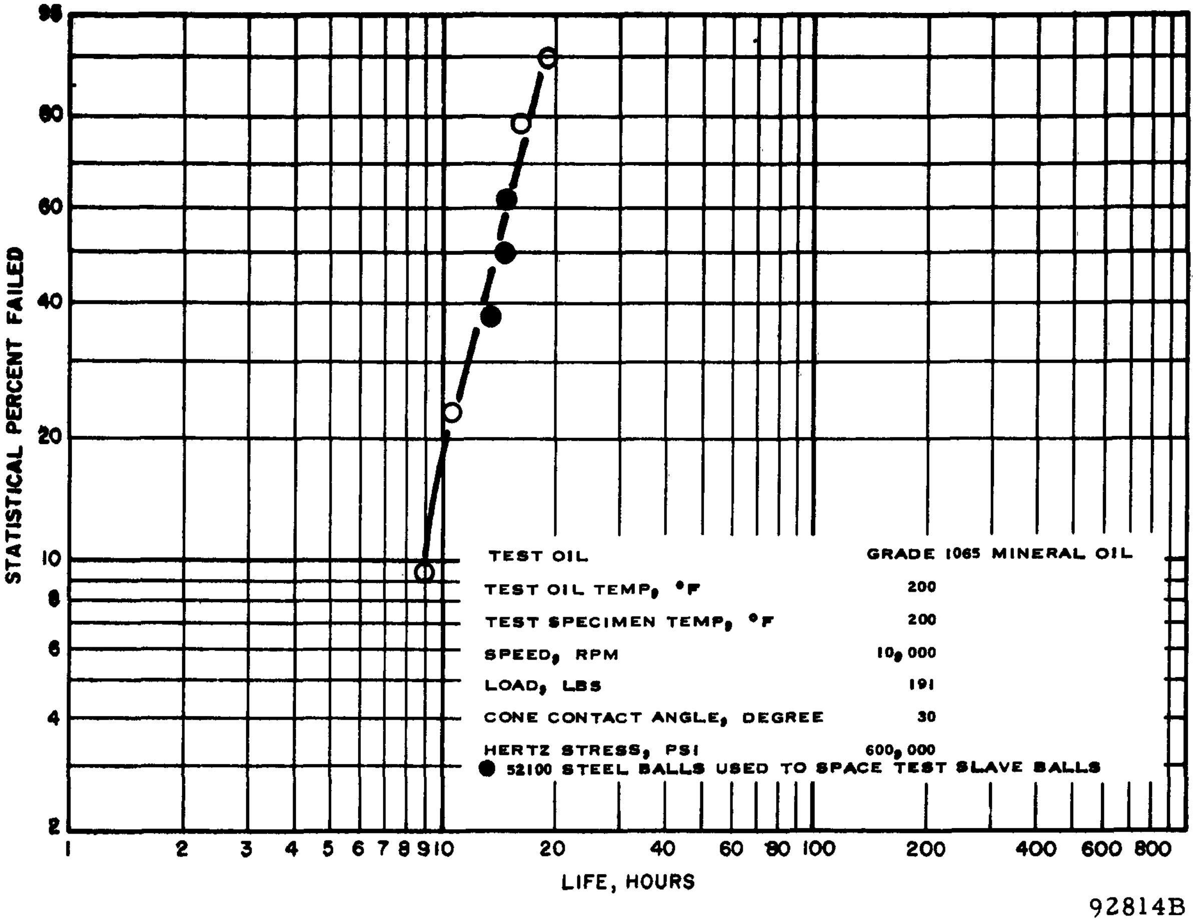

FIGURE 29. WEIBULL PLOT FOR PRELIMINARY TESTS ON 3-BALL/CONE FATIGUE TESTER

VI. SUMMARY

A total of 63 lubricants were studied over the period of May 1, 1962 through October 31, 1964, under Contracts AF 33(657)-9248 and AF 33 (657)-11028. The work conducted under Contract AF 33(657)-9248 was described in a previous summary report.[1] The present summary report is concerned primarily with the accomplishments under Contract AF 33(657)-11028. However, in order to provide an overall view of the performance characteristics of the various lubricants evaluated, it has been necessary, throughout this report, to compare the key results obtained under both contracts. The purpose of this concluding chapter is to condense further the test results on candidate lubricants of potential interest, so that the maximum performance capabilities of these fluids can be readily assessed.

Not all of the lubricants tested over the 30-month period can properly be termed "candidate lubricants" for the supersonic transport engine. Roughly one-third of those included in this program were studied primarily to aid in the development of the various test apparatus and test methods. Roughly another third of the total number of the fluids were evaluated on a fairly limited scale and excluded from further studies, generally on the basis of poor performance shown in those tests conducted under this program, and occasionally on the basis of other information available to the RTD project engineer. Therefore, by process of elimination, only about one-third of the total number were evaluated extensively, except in those instances where only a limited supply was available. Of these, only eight are considered to be of potential interest to supersonic transport engine application on the basis of the data obtained. Table 56 presents a summary of the limiting performance of these eight candidate lubricants.

Before examining the test results, it is well to review first, even if very briefly, the basic approach employed in this program. It was emphasized earlier[1] that since the supersonic transport engine had yet to be developed and since its design features and lubrication requirements were not adequately known, only some broad guidelines were available for lubricant test method development and lubricant screening. These guidelines were: (1) that emphasis would be in the 450 to 500°F bulk oil temperature range corresponding to a projected cruising speed of Mach 2.5 to 3, and (2) that lubricant performance in an oxidative atmosphere would be emphasized, since the lubrication system would be vented to the atmosphere. On the basis of these premises, higher temperature tests were developed by relying heavily upon the proven concepts employed in the screening of lubricants for past and current aviation gas turbine engines (which are vented to the atmosphere).

TABLE 56. SUMMARY OF TEST RESULTS ON CANDIDATE LUBRICANTS OF POTENTIAL INTEREST

Oil Code	Viscosity, cs		O-C(a)	Deposits and Degradation(b)		Load-Carrying Capacity, lb/in.		Corrosion(d)
	100°F	210°F	Max °F	Max °F Sump/Bearing	Oil Changes Required	165°F	Minimum(c)	
O-62-25	15.6	3.5	<425	450/475	0	1800(e)	560(e)	Ag
ATL-403	27.8	5.2	475	<500/550	2	--	--	
ATL-307	286.9	25.7	>600	<500/588	0	>2540	230	Al, Ti, Ag, S, SS
O-64-13	28.4	5.3	425	<525/575	3	2110	1280	
ATL-402	46.8	8.2	450	500/550	1	2370(f)	1870(f)	
ATL-401	26.3	5.1	425	500/575	2	1940(g)	1540(g)	
H-1001	27.5	5.1	<425	525/575	2	2080	600	
F-1041	354.5	12.9	>600	600/650	0	2460	1040	Cu

(a) The temperature given represents the maximum temperature at which no more than 100 percent viscosity increase was obtained in the 18-hr oxidation-corrosion test.

(b) The temperatures given represent the maximum temperature conditions at which no more than 60 was obtained for an overall deposit rating in the 48-hr lubricant deposits and degradation test, with no more than 3 oil changes.

(c) Occurring in gear temperature range of 400 to 500°F.

(d) Denotes metal specimen weight changes of ±0.20 mg/cm^2 or more.

(e) Results from O-60-26, an earlier batch of O-62-25.

(f) Results from ATL-304, an earlier batch of ATL-402.

(g) Results from ATL-305, an earlier batch of ATL-401.

Another objective of this program was to provide a basis for screening candidate lubricants prior to submitting them to engine testing. Since no engine test data would be available to correlate with the screening tests data, the specific conditions for the screening tests could not realistically be established. Therefore, the only logical approach in lubricant screening at this stage would be to attempt to establish the maximum performance capabilities of the candidate lubricants on the basis of broad-spectrum test data over a wide range of test conditions. It is to be understood that the limiting performance of the lubricants so established in the screening tests may not be adequate to define the performance of the same lubricants in actual engine operation (and the same situation exists with the current lubricant screening tests with respect to lubricant performance in current engines). That is, of course, the reason why actual engine testing is always a necessary and final step in lubricant evaluation. The screening tests are, therefore, primarily intended to rank lubricants in relative order. The final selection of lubricants must necessarily be based on engine testing, as well as on such other considerations as cost and availability which are beyond the scope of this program.

In general, the sequence of lubricant screening in this program was as follows: First, a candidate lubricant was evaluated in the 18-hr oxidation-corrosion test at 425°F and then at increasing temperature increments of 25°F to establish the maximum sample temperature that would yield no more than a 100 percent viscosity increase. The 18-hr oxidation-corrosion test was employed because it was known from earlier work(4) that the 425°F 18-hr oxidation-corrosion test gave good correlation with the 425°F MIL-L-9236 engine test on a wide variety of lubricants. It was reasoned that extension of the temperature scale, using basically the same test concept otherwise, was the only logical way for lubricant screening at higher temperatures.

With the oxidation-corrosion test data as a guide, the promising candidate lubricants were then evaluated for lubricant deposits and degradation in the bearing test. The bearing test was selected for this purpose because of its wide acceptance in industry(5). It was reasoned that extension of the temperature scale, using basically the same test concept otherwise, was the only logical way for screening lubricants at higher temperatures. However, the test duration employed in this program was only 48 hr, rather than 100 hr as used in the current bearing tests. This expedient was adopted for reason of economy of time, since the relative ranking of lubricants was the primary information desired. By means of the 48-hr lubricant deposits and degradation test, the maximum test oil sump temperature and maximum bearing temperature capability of each candidate lubricant, that would result

in an overall deposit rating of no more than 60 with no more than three oil changes due to 100 percent viscosity increases, was determined. These determinations were usually initiated at a sump temperature equal to the maximum sample temperature established in the oxidation-corrosion test and at a bearing temperature 50°F higher than the sump temperature, following which the sump and bearing temperatures were increased in 25°F steps. However, considerable variations from this procedure were allowed in the interest of conserving time and when the lubricant supply was limited.

Finally, gear tests were conducted at 165, 425, 500, and 600°F test conditions to determine the variation of gear load-carrying capacity of each promising candidate with temperature and, in particular, its minimum load-carrying capacity. The gear load-carrying capacity test concept was again an established one[6], except that Nitralloy N steel test gears were used and that the test gears were heated to the desired test temperature because it was found that gear load-carrying capacity was strongly influenced by gear material and temperature[1] and thus must be taken into account.

In Table 56, key test results for eight candidate lubricants of potential interest are summarized. The table includes: (a) lubricant viscosities at 100 and 210°F, (b) the maximum lubricant (sample) temperature at which no more than 100 percent viscosity increase was obtained in the 18-hr oxidation-corrosion test, (c) the maximum lubricant sump temperature and bearing temperature combination at which an overall deposit rating of no more than 60 was obtained with no more than three oil changes in the 48-hour lubricant deposits and degradation test, and the number of oil changes required, (d) the gear load-carrying capacity of the lubricant at 165°F test conditions, and the minimum load-carrying capacity of the lubricant (occurring within the gear temperature range of 400 to 500°F), and (e) the corrosion tendency of the lubricant as shown for either the oxidation-corrosion test or the lubricant deposits and degradation test, based on metal specimen weight changes of ± 0.20 mg/cm^2 or more.

Table 56 presents a summary of the test results on the eight lubricants ranked in accordance to their maximum performance capabilities on the basis of the lubricant deposits and degradation test. A description of these lubricants is given in Table 57 in the Appendix.

Lubricant O-62-25 exhibits only borderline high-temperature capability among those listed in Table 56. It gives a deposit rating of 35 at 450°F sump and 475°F bearing temperatures, and a deposit rating of 121 at 450°F sump and 500°F bearing temperatures, in both instances requiring no oil changes in the 48-hr bearing test (see Table 44). Its gear load-carrying capacity of 1800 lb/in. at 165°F and 560 lb/in. at 400°F is only modest. Further, it shows significant corrosion of silver.

F-1041, the 5P4E polyphenyl ether, has the highest temperature capability of those listed in Table 56. It gives a deposit rating of 48 (average of two tests, Table 42) with no oil change in 48-hr, at 600°F sump and 650°F bearing temperatures. At 650°F sump and 700°F bearing temperatures, the deposit rating is 77 (average of two tests), again with no oil changes in 48 hr. Its gear load-carrying capacity of 2460 lb/in. at 165°F and 1040 lb/in. at 425°F is good. However, it shows significant attack on copper, and it has a high pour point (40°F) and high viscosity.

The other six fluids are seen to fall between O-62-25 and F-1041 in high-temperature capability. Among these, ATL-403 gives a deposit rating of 116 at 500°F sump and 550°F bearing temperatures, requiring two oil changes in 48 hr (Table 44). From general experience, it is believed that this fluid could give a deposit rating less than 60 at 475°F sump and 525°F bearing temperatures. However, because of insufficient supply, no additional bearing test was run, nor was the gear load-carrying capacity determined.

While ATL-307 is shown to be more than adequate from the standpoint of oxidation resistance, its very low gear load-carrying capacity at high temperature and its corrosive action on all of the metals included in the tests (in addition to the etching of glassware used in the oxidation-corrosion test) more than outweigh its oxidative stability. Its deposit rating of 112 at 500°F sump and 588°F bearing temperatures (Table 44) was largely due to accumulation of the corrosion products.

O-64-13 gives a deposit rating of 135 at 525°F sump and 575°F bearing temperatures, requiring three oil changes in 48 hr (Table 44). From general experience, it is believed that this fluid could give a deposit rating less than 60 at 500°F sump and 550°F bearing temperatures. Unfortunately, no additional bearing test was run on account of short lubricant supply. Its gear load-carrying capacity of 2110 lb/in. at 165°F and 1280 lb/in. at 425°F is good.

ATL-402 gives a deposit rating of 39 at 500°F sump and 550°F bearing temperatures, requiring one oil change in 48 hr (Table 44). However, at 525°F sump and 575°F bearing temperatures, it gives a deposit rating of 104 with two oil changes. These results check very well with those obtained from ATL-304, an earlier batch of the same formulation. Its load-carrying capacity of 2370 lb/in. at 165°F and 1870 lb/in. at 425°F (for ATL-304) is the best shown in Table 56.

ATL-401 has a slightly higher temperature capability than ATL-402. It gives a deposit rating of 45 at 500°F sump and 575°F bearing temperatures, requiring two oil changes in 48 hr. At 525°F sump and 575°F bearing temperatures, its deposit rating is 57, but it requires four oil changes in 48 hr.

These results again check very well with those obtained from ATL-305, an earlier batch of the same formulation. Its gear load-carrying capacity of 1940 lb/in. at 165°F and 1540 lb/in. at 425°F (for ATL-305) is only slightly inferior to that of ATL-402.

H-1001 gives a high-temperature capability next to F-1041, the 5P4E polyphenyl ether. At 525°F sump and 575°F bearing temperatures, it gives a deposit rating of 60.5 (average of seven tests, Table 44), requiring two oil changes in 48 hr. At 550°F sump and 600°F bearing temperatures, it gives a deposit rating of 102, with four oil changes in 48 hr. Its gear load-carrying capacity of 2080 lb/in. at 165°F and 600 lb/in. at 500°F is, however, rather modest.

In conclusion, considering all of the data presented in Table 56 but ignoring the high pour point, high viscosity, and copper corrosion of F-1041, and not considering cost and availability, the fluids showing the best promise for supersonic transport engine application are:

F-1041
H-1001
ATL-401
ATL-402
O-64-13

If F-1041 is eliminated for its high pour point, high viscosity, and copper corrosion, then, not considering cost and availability, the fluids showing the best promise are:

H-1001
ATL-401
ATL-402
O-64-13

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3. Bisson, E. E., Anderson, W. J., "Advanced Bearing Technology," National Aeronautics and Space Administration Publication SP-38, 1964.

4. Lubrication Research and Test Method Development for Aerospace Propulsion Systems, Progress Report No. 5 (July 5, 1961 to October 30, 1961)," SwRI Report No. RS-343, October 30, 1961.

5. "Aviation Gas Turbine Lubricants," SAE Special Publication 234, October 1962.

6. "Lubricants, Liquid Fuels and Related Products; Method of Testing," Federal Test Method Standard No. 791a, Method 6511, December 31, 1961.

APPENDIX

TABLE 57. DESCRIPTION OF TEST LUBRICANTS

Oil Code	Viscosity, cs 100°F	210°F	Description
Ref. Oil B	237.8	20.3	Mineral oil, MIL-L-6082B, Grade 1100
E-1022	11.4	2.7	Polyglycol
F-1041	354.5	12.9	Polyphenyl ether, 5P4E mixed isomers
F-1055	103.0	11.5	Mineral oil, MIL-L-6082B, Grade 1065
G-1049	45.7	15.3	Silicone (chlorinated)
H-1001	27.5	5.1	MIL-L-23699 type
H-1026	13.1	3.3	MIL-L-7808C type
GTO-615	61.3	20.7	Silicone (chlorinated)
GTO-770	64.4	10.9	Polyglycol
GTO-880	13.4	3.4	MIL-L-7808C type
LRO-8	70.9	6.3	Polyphenyl ether, 4P3E mixed isomers
LRO-13	362.4	13.2	Polyphenyl ether, 5P4E mixed isomers
O-58-24	34.7		MIL-L-9236A type
O-59-15	18.7		MIL-L-9236B type
O-59-26	18.7		MIL-L-9236B type
O-60-12	16.1		MIL-L-9236B
O-60-19	20.8		MIL-L-9236B type
O-60-23	16.0	3.6	MIL-L-9236B
O-60-26	15.0	3.5	MIL-L-9236B
O-60-27	15.0	3.4	Different batch of O-60-26
O-61-19	15.7		Different batch of O-60-26
O-61-20	357.3	13.2	Polyphenyl ether, 5P4E mixed isomers
O-62-25	15.6	3.5	Different batch of O-60-26
O-63-26	27.6	5.0	MIL-L-23699 type
O-64-13	28.4	5.3	MIL-L-23699 type
O-64-17	28.4	5.3	MIL-L-23699 type
MLO-61-1011	16.2	3.6	Different batch of O-60-23
MLO-62-1005	41.8	6.8	Advanced turbine oil candidate
MLO-62-1008	64.7	7.9	Advanced turbine oil candidate
MLO-62-1011	14.8	3.4	MIL-L-9236B type
MLO-62-1012	26.8	5.3	Advanced turbine oil candidate
MLO-62-1013	28.2	5.5	Advanced turbine oil candidate
MLO-63-1001	46.8		Advanced turbine oil candidate
ATL-304	47.1	8.2	Advanced turbine oil candidate
ATL-305	26.2	5.1	Advanced turbine oil candidate
ATL-306	27.5	5.2	Advanced turbine oil candidate
ATL-307	286.9	25.7	Advanced turbine oil candidate
ATL-308	49.0	7.9	Advanced turbine oil candidate
ATL-309	43.1	6.0	Advanced turbine oil candidate
ATL-401	26.3	5.1	Different batch of ATL-305
ATL-402	46.8	8.2	Different batch of ATL-304
ATL-403	27.8	5.2	Advanced turbine oil candidate
ATL-404	29.6	5.4	Advanced turbine oil candidate
ATL-405	34.4	6.3	Advanced turbine oil candidate
ATL-406	26.9	5.2	Advanced turbine oil candidate

Information on additional fluids investigated during the first year is given in the Appendix of Part I of this report.

TABLE 58. RESULTS OF 425°F OXIDATION-CORROSION TESTS ON H-1001

CRC Test Method, Air Tube	Test Sample Analysis	Test Time, hours 0	16	24	40	48	Oil Loss, wt %	Overhead Sample Acidity, mg KOH/g	Overhead Sample Vis, cs/100°F
A, diffuser	Vis, cs at 100°F	27.50	31.54	32.65	36.88	48.50	4		
	% Vis Increase	-	14.7	18.7	34.1	76.4			
	NN, mg KOH/g	0.07	0.95	1.32	5.29	13.81			
A, diffuser	Vis, cs at 100°F	27.50	31.95	32.75	43.68	54.01	4		
	% Vis Increase	-	16.2	19.1	58.8	96.4			
	NN, mg KOH/g	0.07	0.82	1.21	14.67	15.53			
A, diffuser	Vis, cs at 100°F	27.50	31.62	32.47	42.66	50.16	5		
	% Vis Increase	-	15.0	18.0	55.1	82.4			
	NN, mg KOH/g	0.07	0.79	0.93	12.59	14.40			
A, open	Vis, cs at 100°F	27.50	31.48	32.28	34.06	35.08	3		
	% Vis Increase	-	14.5	17.4	23.9	27.6			
	NN, mg KOH/g	0.07	0.83	1.13	1.73	3.18			
A, open	Vis, cs at 100°F	27.50	31.64	32.44	34.07	35.77	4		
	% Vis Increase	-	15.1	18.0	23.9	30.1			
	NN, mg KOH/g	0.07	0.83	1.09	1.62	3.18			
A, open	Vis, cs at 100°F	27.50	31.54	32.35	34.04	34.95	2		
	% Vis Increase	-	14.7	17.6	23.8	27.1			
	NN, mg KOH/g	0.07	0.82	1.20	1.97	3.13			
B, diffuser	Vis, cs at 100°F	27.50	33.32	739.8	(a)		53	124.0	10.02
	% Vis Increase	-	21.2	2590	-				
	NN, mg KOH/g	0.07	0.64	34.1	-				
	Overhead Wt, g	-	21.9	59.9	69.6				
B, diffuser	Vis, cs at 100°F	27.50	33.66	372.6	(a)		50	123.1	9.72
	% Vis Increase	-	22.4	1255	-				
	NN, mg KOH/g	0.07	0.57	32.6	-				
	Overhead Wt, g	-	20.0	53.5	66.8				
B, diffuser	Vis, cs at 100°F	27.50	33.73	323.1	(a)		50	122.0	9.92
	% Vis Increase	-	22.7	1075	-				
	NN, mg KOH/g	0.07	0.54	30.7	-				
	Overhead Wt, g	-	20.8	52.0	67.3				
B, open	Vis, cs at 100°F	27.50	33.04	36.17	321.4	1552	45	44.0	16.89
	% Vis Increase	-	20.1	31.5	1070	5550			
	NN, mg KOH/g	0.07	0.56	1.57	13.20	15.3			
	Overhead Wt, g	-	22.8	32.0	57.3	59.8			
B, open	Vis, cs at 100°F	27.50	33.42	36.02	289.6	1081	46	44.4	16.78
	% Vis Increase	-	21.5	31.0	953	3830			
	NN, mg KOH/g	0.07	0.59	0.83	11.78	14.30			
	Overhead Wt, g	-	20.8	28.7	51.3	53.8			
B, open	Vis, cs at 100°F	27.50	33.29	37.34	456.4	2392	46	48.8	16.51
	% Vis Increase	-	21.1	35.8	1560	8600			
	NN, mg KOH/g	0.07	0.56	2.05	13.59	15.67			
	Overhead Wt, g	-	23.0	32.4	60.1	62.9			

(a) Test terminated at 40 hr, sample semi-solid. Severe foaming occurred at 22 hr; foaming subsided after withdrawal of 24-hr sample.

TABLE 59. METAL SPECIMEN WEIGHT CHANGE FOR 425°F OXIDATION-CORROSION TESTS WITH H-1001

CRC Test Method, Air Tube	Weight Change, mg/cm² at 48 hr						
	Al	Ag	Cu	Steel	SS	Mg	Ti
A, diffuser	0.0	-0.2	-0.1	+0.1	-	-17.2	0.0
	0.0	-0.1	-0.2	+0.1	-	-19.3	+0.1
	0.0	-0.1	-0.1	+0.1	-	-16.2	0.0
A, open	0.0	+0.1	0.0	+0.1	-	0.0	-0.1
	-0.1	+0.1	-0.1	+0.1	-	0.0	-0.1
	-0.1	+0.2	-0.1	0.0	-	0.0	-0.1
B, diffuser	0.0[a]	0.0	-1.0	+0.1	0.0	-	-0.2
	0.0[a]	-0.2	0.0	+0.1	+0.1	-	0.0
	0.0[a]	-0.1	0.0	0.0	0.0	-	-0.1
B, open	-0.1	0.0	-0.5	0.0	0.0	-	-0.2
	-0.1	0.0	-0.3	+0.1	0.0	-	-0.1
	-0.2	0.0	-0.4	0.0	+0.1	-	-0.2

(a) Tests terminated at 40 hr.

TABLE 60. RESULTS OF 450°F OXIDATION-CORROSION TESTS ON ATL-305

CRC Test Method, Air Tube	Test Sample Analysis	Test Time, hours 0	16	24	40	48	Oil Loss, wt %	Overhead Sample Acidity, mg KOH/g	Overhead Sample Vis, cs/100°F
A, diffuser	Vis, cs at 100°F	26.22	35.83	40.58	62.24	112.4	15		
	% Vis Increase	-	36.7	54.8	137	329			
	NN, mg KOH/g	0.09	7.27	9.07	11.98	12.04			
A, diffuser	Vis, cs at 100°F	26.22	35.22	39.66	57.37	83.19	10		
	% Vis Increase	-	34.3	51.3	119	217			
	NN, mg KOH/g	0.09	7.68	10.26	11.70	13.22			
A, diffuser	Vis, cs at 100°F	26.22	36.45	40.61	56.76	89.14	19		
	% Vis Increase	-	39.0	54.9	116	240			
	NN, mg KOH/g	0.09	6.57	8.78	12.28	12.65			
A, open	Vis, cs at 100°F	26.22	33.81	37.76	51.90	79.60	6		
	% Vis Increase	-	29.0	44.0	98.0	204			
	NN, mg KOH/g	0.09	1.91	2.56	5.65	6.70			
A, open	Vis, cs at 100°F	26.22	33.66	37.47	49.20	69.36	3		
	% Vis Increase	-	28.4	42.9	87.6	165			
	NN, mg KOH/g	0.09	2.15	2.54	4.76	6.68			
A, open	Vis, cs at 100°F	26.22	33.04	36.54	44.96	55.34	5		
	% Vis Increase	-	26.0	39.4	71.5	111			
	NN, mg KOH/g	0.09	1.74	2.39	3.81	7.66			
B, diffuser	Vis, cs at 100°F	26.22	50.63[a]	76.99	653.4	(b)	54	(c)	(c)
	% Vis Increase	-	93.1	194	2390	-			
	NN, mg KOH/g	0.09	1.57	2.89	7.17	-			
	Overhead Wt, g	-	6.1	9.5	21.6	26.3			
B, diffuser	Vis, cs at 100°F	26.22	49.73[a]	70.12	231.1	(d)	37	47.6	15.72
	% Vis Increase	-	90.6	167.0	781				
	NN, mg KOH/g	0.09	1.46	2.88	5.49				
	Overhead Wt, g	-	9.0	12.8	16.0				
B, diffuser	Vis, cs at 100°F	26.22	48.76[a]	69.90	252.3	(b)	51	41.6	18.54
	% Vis Increase	-	86.0	167	862	-			
	NN, mg KOH/g	0.09	1.47	2.33	4.83	8.34			
	Overhead Wt, g	-	7.2	10.1	15.0	20.9			
B, open	Vis, cs at 100°F	26.22	52.15	78.11	428.9	4130	59	(c)	(c)
	% Vis Increase	-	98.9	198	1536	14,650			
	NN, mg KOH/g	0.09	1.30	2.29	4.67	5.78			
	Overhead Wt, g	-	39.7	54.4	72.0	75.7			
B, open	Vis, cs at 100°F	26.22	53.63	82.95	526.2	>3500	61	36.2	15.87
	% Vis Increase	-	105	216	1905	>10,000			
	NN, mg KOH/g	0.09	1.45	2.32	5.56	7.26			
	Overhead Wt, g	-	40.1	59.0	75.0	77.5			
B, open	Vis, cs at 100°F	26.22	52.71	83.30	582.7	(b)	59	36.7	16.08
	% Vis Increase	-	101	218	2100	-			
	NN, mg KOH/g	0.09	1.35	2.39	4.53	7.92			
	Overhead Wt, g	-	43.2	58.0	74.8	76.0			

(a) Foaming up to bottom of test cell head after 1 hr, continuing until the end of test.

(b) Sample too thick to determine values.

(c) No representative overhead samples were obtained.

(d) Test discontinued at 40 hr.

TABLE 61. METAL SPECIMEN WEIGHT CHANGE FOR 450°F OXIDATION-CORROSION TESTS WITH ATL-305

CRC Test Method, Air Tube	Weight Change, mg/cm² at 48 hr						
	Al	Ag	Cu	Steel	SS	Mg	Ti
A, diffuser	+0.1	-0.1	-27.5	0.0	-	(a)	+0.1
	0.0	+0.1	-25.9	+0.1	-	(a)	0.0
	+0.1	-0.1	-25.2	-0.1	-	(a)	-0.1
A, open	0.0	-0.1	-8.5	-0.2	-	-36.1	0.0
	+0.1	+0.1	-7.0	+0.2	-	-35.2	0.0
	-0.1	-0.2	-5.7	0.0	-	-25.7	-0.1
B, diffuser	0.0	-0.1	-6.1	0.0	0.0	-	0.0
	0.0[b]	-0.1	-6.0	+0.1	0.0	-	0.0
	-0.1	-0.1	-6.0	0.0	+0.1	-	0.0
B, open	0.0	-0.1	-4.7	0.0	0.0	-	0.0
	0.0	0.0	-6.9	+0.1	-0.1	-	0.0
	0.0	0.0	-4.3	-0.1	+0.1	-	0.0

(a) Specimen totally destroyed.

(b) Test terminated at 40 hr.

TABLE 62. RESULTS OF 450°F OXIDATION-CORROSION TESTS ON ATL-401

CRC Test Method, Air Tube	Test Sample Analysis	Test Time, hours 0	16	24	40	48	Oil Loss, wt %	Overhead Sample Acidity, mg KOH/g	Overhead Sample Vis, cs/100°F
A, diffuser	Vis, cs at 100°F	26.30	36.00	40.62	62.71	103.6	15		
	% Vis Increase	-	36.9	54.4	138	294			
	NN, mg KOH/g	0.11	5.55	6.77	9.33	9.66			
A, diffuser	Vis, cs at 100°F	26.30	36.82	41.99	68.68	110.6	19		
	% Vis Increase	-	40.0	60.0	161	320			
	NN, mg KOH/g	0.11	4.98	7.24	10.40	10.43			
A, diffuser	Vis, cs at 100°F	26.30	38.30	43.53	70.31	194.0	19		
	% Vis Increase	-	45.6	65.5	167	635			
	NN, mg KOH/g	0.11	4.50	4.57	5.07	7.15			
A, open	Vis, cs at 100°F	26.30	33.73	37.45	49.63	72.08	9		
	% Vis Increase	-	28.3	42.4	88.7	174			
	NN, mg KOH/g	0.11	2.05	2.36	4.90	7.93			
A, open	Vis, cs at 100°F	26.30	32.63	35.16	42.39	51.45	7		
	% Vis Increase	-	24.1	33.7	61.2	95.6			
	NN, mg KOH/g	0.11	1.71	2.21	3.88	6.20			
A, open	Vis, cs at 100°F	26.30	33.76	37.02	47.42	65.21	8		
	% Vis Increase	-	28.4	40.8	80.3	148			
	NN, mg KOH/g	0.11	1.90	3.20	5.64	7.27			
B, diffuser	Vis, cs at 100°F	26.30	47.92[a]	65.47	193.8	(b)	49	40.9	17.73
	% Vis Increase	-	82.2	149	637	-			
	NN, mg KOH/g	0.11	1.22	2.42	3.96	7.15			
	Overhead Wt, g	-	8.3	11.5	16.7	23.5			
B, diffuser	Vis, cs at 100°F	26.30	50.08[a]	70.04	234.2	2365	52	44.4	17.70
	% Vis Increase	-	90.4	166	790	8900			
	NN, mg KOH/g	0.11	1.86	3.74	5.61	8.13			
	Overhead Wt, g	-	8.7	11.5	16.1	22.0			
B, diffuser	Vis, cs at 100°F	26.30	49.51[a]	70.13	264.9	(b)	52	40.5	17.79
	% Vis Increase	-	88.3	167	905	-			
	NN, mg KOH/g	0.11	1.65	3.29	5.89	8.46			
	Overhead Wt, g	-	11.3	15.5	21.2	27.5			
B, open	Vis, cs at 100°F	26.30	51.58	80.87	570.8	(b)	58	35.7	15.93
	% Vis Increase	-	96.1	207	2000	-			
	NN, mg KOH/g	0.11	1.41	2.36	5.06	8.10			
	Overhead Wt, g	-	42.7	57.4	73.8	74.6			
B, open	Vis, cs at 100°F	26.30	54.28	85.57	598.3	(b)	58	37.9	16.14
	% Vis Increase	-	106	225	2175	-			
	NN, mg KOH/g	0.11	1.90	3.39	5.04	8.11			
	Overhead Wt, g	-	44.7	59.0	74.1	75.5			
B, open	Vis, cs at 100°F	26.30	55.09	86.66	725.7	(b)	61	34.8	16.31
	% Vis Increase	-	109	230	2660	-			
	NN, mg KOH/g	0.11	2.09	3.42	5.57	8.53			
	Overhead Wt, g	-	45.0	60.1	75.3	76.3			

(a) Foaming up to bottom of test cell head after 1 hr, continuing until the end of test.

(b) Insufficient sample.

TABLE 63. METAL SPECIMEN WEIGHT CHANGE FOR 450°F OXIDATION-CORROSION TESTS WITH ATL-401

CRC Test Method, Air Tube	Weight Change, mg/cm^2 at 48 hr						
	Al	Ag	Cu	Steel	SS	Mg	Ti
A, diffuser	0.0	0.0	-26.0	-0.1	-	(a)	0.0
	0.0	+0.2	- 9.8	0.0	-	(a)	-0.2
	0.0	+0.2	-15.0	0.0	-	(a)	-0.2
A, open	-0.1	-0.2	- 7.2	0.0	-	-34.0	0.0
	+0.1	+0.2	- 5.7	+0.1	-	-26.9	+0.1
	+0.1	0.0	- 6.6	+0.1	-	-31.3	0.0
B, diffuser	0.0	-0.3	- 5.8	-0.1	+0.1	-	0.0
	0.0	-0.2	- 5.9	+0.1	-0.1	-	-0.1
	0.0	-0.1	- 5.8	+0.1	0.0	-	-0.1
B, open	-0.1	0.0	- 4.0	0.0	+0.2	-	0.0
	0.0	+0.2	- 3.9	+0.1	0.0	-	-0.2
	+0.1	-0.1	- 4.5	0.0	+0.1	-	-0.2

(a)Specimen totally destroyed.

TABLE 64. SUMMARY DATA ON F-1041, BEARING TEST NO. 16

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	48	2	96
Heater Mount (F)	75	3	225
Heater Mount (R)	48.5	3	145.5
Seal Plate	12	1	12
Test Bearing	52	5	260
			738.5

Overall Rating: 738.5/6 = 123.1

Not included in official rating: Sump-wall 100% clean
bottom 100% clean

Oil consumption rate: 198 ml/hr

Total accumulated filter wt: Pressure 1.2 g Scavenge 1.4 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.07	1.5
8	13.30	3.3
12	13.35	3.6
16	13.50	4.8
20	13.60	5.6
24	13.76	6.8
28	13.97	8.5
32	14.07	9.2
36	14.17	10.0
40	14.27	10.8
44	14.32	11.2
48	14.51	12.7

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	600
Oil-in temp, °F	594
Bearing temp, °F	750
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1

TABLE 65. SUMMARY DATA ON F-1041, BEARING TEST NO. 17

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	54	2	108
Heater Mount (F)	64.5	3	193.5
Heater Mount (R)	78.5	3	235.5
Seal Plate	0	1	0
Test Bearing	41.3	5	206.5
			743.5

Overall Rating: 743.5/6 = 123.9

Not included in official rating: Sump-wall 100% clean
bottom 100% clean

Oil consumption rate: 135 ml/hr

Total accumulated filter wt: Pressure 2.4 g Scavenge 2.8 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.03	1.2
8	13.35	3.6
12	13.65	6.0
16	14.05	9.1
20	14.22	10.4
24	14.53	12.8
28	14.73	14.4
32	14.98	16.3
36	15.33	19.0
40	15.58	21.0
44	15.93	23.7
48	16.13	25.2

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	600
Oil-in temp, °F	591
Bearing temp, °F	750
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 66. SUMMARY DATA ON F-1041, BEARING TEST NO. 18

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	51	2	102
Heater Mount (F)	87.5	3	262.5
Heater Mount (R)	91	3	273
Seal Plate	0	1	0
Test Bearing	44.5	5	222.5
			860

Overall Rating: 860/6 = 143.3

Not included in official rating: Sump-wall 100% clean
bottom 100% clean

Oil consumption rate: 104 ml/hr

Total accumulated filter wt: Pressure 1.5 g Scavenge 1.6 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.11	1.8
8	13.45	4.4
12	13.58	5.4
16	13.95	8.3
20	13.95	8.3
24	14.37	11.6
28	14.58	13.2
32	14.87	15.5
36	15.19	17.9
40	15.60	21.1
44	15.69	21.8
48	16.53	28.3

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	600
Oil-in temp, °F	591
Bearing temp, °F	750
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 67. SUMMARY DATA ON F-1041, BEARING TEST NO. 20

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	45	2	90
Heater Mount (F)	63.5	3	190.5
Heater Mount (R)	43.5	3	130.5
Seal Plate	6	1	6
Test Bearing	45.3	5	226.5
			643.5

Overall Rating: 643.5/6 = 107.3

Not included in official rating: Sump-wall 20%L varnish, 80% clean
bottom 100% clean

Oil consumption rate: 333 ml/hr

Total accumulated filter wt: Pressure 2.4 g Scavenge 1.7 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.04	1.2
8	14.23	10.5
12	15.56	20.8
16	17.36	34.8
20	18.30	43.6
24	21.55	67.3
28	23.55	82.8
32*	32.28	151
36	14.18	10.1
40	16.88	31.1
44	22.56	75.2
48	28.33	120

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	700
Oil-in temp, °F	686
Bearing temp, °F	750
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1

*Test oil changed at 32 hr due to viscosity increase.

TABLE 68. SUMMARY DATA ON F-1041, BEARING TEST NO. 21

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	51	2	102
Heater Mount (F)	21.5	3	64.5
Heater Mount (R)	28.5	3	85.5
Seal Plate	0	1	0
Test Bearing	41	5	205
			457

Overall Rating: 457/6 = 76.2

Not included in official rating: Sump-wall 100% clean
bottom 100% clean

Oil consumption rate: 171 ml/hr

Total accumulated filter wt: Pressure 1.4 g Scavenge 1.4 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.33	3.5
8	13.77	6.9
12	14.11	9.5
16	14.62	13.5
20	14.83	15.1
24	15.62	21.3
28	16.18	25.6
32	17.48	35.7
36	18.74	45.5
40	19.97	55.0
44	22.42	74.1
48	25.32	96.6

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	650
Oil-in temp, °F	638
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1

TABLE 69. SUMMARY DATA ON F-1041, BEARING TEST NO. 22

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	45	2	90
Heater Mount (F)	116	3	348
Heater Mount (R)	53.5	3	160.5
Seal Plate	6	1	6
Test Bearing	46.2	5	231
			835.5

Overall Rating: 835.5/6 = 139.3

Not included in official rating: Sump-wall 100% clean
bottom 100% clean

Oil consumption rate: 123 ml/hr

Total accumulated filter wt: Pressure 1.6 g Scavenge 1.8 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.17	2.3
8	13.46	4.5
12	13.72	6.5
16	14.09	9.4
20	14.00	8.7
24	14.44	12.1
28	14.30	11.0
32	14.68	14.0
36	14.70	14.1
40	14.96	16.1
44	15.19	17.9
48	15.29	18.7

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	600
Oil-in temp, °F	593
Bearing temp, °F	750
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1

TABLE 70. SUMMARY DATA ON F-1041, BEARING TEST NO. 23

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	15	2	30
Heater Mount (F)	55.5	3	166.5
Heater Mount (R)	49	3	147
Seal Plate	6	1	6
Test Bearing	45	5	225
			574.5

Overall Rating: 574.5/6 = 95.8

Not included in official rating: Sump-wall 20% M varnish, 80% clean
bottom 100% clean

Oil consumption rate: 196 ml/hr

Total accumulated filter wt: Pressure 1.4 g Scavenge 1.4 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.42	4.2
8	15.50	20.3
12	18.40	42.9
16*	23.04	78.9
20	14.66	13.8
24	17.26	34.0
28	21.18	64.4
32*	13.20	2.5
36	15.72	22.0
40	19.25	49.5
44	25.36	96.9
44.5	25.62	98.9

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	700
Oil-in temp, °F	687
Bearing temp, °F	750
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 17 and 32 hr due to viscosity increase.

TABLE 71. SUMMARY DATA ON F-1041, BEARING TEST NO. 24

Demerit Rating

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer & Nut	15	2	30
Heater Mount (F)	39	3	117
Heater Mount (R)	26	3	78
Seal Plate	0	1	0
Test Bearing	41.2	5	206
			431

Overall Rating: 431/6 = 71.8

Not included in official rating: Sump-wall 15% L varnish, 85% clean
bottom 100% clean

Oil consumption rate: 111 ml/hr
Total accumulated filter wt: Pressure 0.8 g Scavenge 0.6 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.18	2.3
8	13.75	6.8
12	14.28	10.9
16	14.86	15.4
20	15.23	18.2
24	15.95	23.8
28	17.14	33.1
32	17.56	36.3
36	18.02	39.9
40	19.43	50.9
44	20.25	57.2
48	21.36	65.8

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	650
Oil-in temp, °F	640
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 72. SUMMARY DATA ON F-1041, BEARING TEST NO. 25

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	12	2	24
Heater Mount (F)	1.2	3	3.6
Heater Mount (R)	9.5	3	28.5
Seal Plate	0	1	0
Test Bearing	33.5	5	167.5
			233.6

Overall Rating: 233.6/6 = 38.9

Not included in official rating: Sump-wall 100% clean
bottom 100% clean

Oil consumption rate: 108 ml/hr

Total accumulated filter wt: Pressure 0.7 g Scavenge 0.5 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.00	0.9
8	13.31	3.3
12	13.34	3.6
16	13.44	4.3
20	13.52	5.0
24	13.56	5.3
28	13.52	5.0
32	13.67	6.1
36	13.72	6.5
40	13.76	6.8
44	13.80	7.1
48	13.88	7.8

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	600
Oil-in temp, °F	589
Bearing temp, °F	650
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1

TABLE 73. SUMMARY DATA ON F-1041, BEARING TEST NO. 26

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	8	2	16
Heater Mount (F)	36	3	108
Heater Mount (R)	8.5	3	25.5
Seal Plate	0	1	0
Test Bearing	41.5	5	207.5
			357

Overall Rating: 357/6 = 59.5

Not included in official rating: Sump-wall 100% clean
bottom 100% clean

Oil consumption rate: 52 ml/hr

Total accumulated filter wt: Pressure 0.6 g Scavenge 0.6 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.04	1.2
8	13.16	2.2
12	13.29	3.2
16	13.42	4.2
20	13.52	5.0
24	13.52	5.0
28	13.66	6.1
32	13.78	7.0
36	13.86	7.6
40	13.92	8.1
44	14.15	9.9
48	14.30	11.0

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	600
Oil-in temp, °F	588
Bearing temp, °F	650
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 74. SUMMARY DATA ON F-1041, BEARING TEST NO. 27

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	13	2	26
Heater Mount (F)	65.5	3	196.5
Heater Mount (R)	49.5	3	148.5
Seal Plate	0	1	0
Test Bearing	34.8	5	174
			545

Overall Rating: 545/6 = 90.8

Not included in official rating: Sump-wall 100% clean
bottom 100% clean

Oil Consumption rate: 85 ml/hr

Total accumulated filter wt: Pressure 0.9 g Scavenge 0.4 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.03	1.2
8	13.21	2.6
12	13.39	4.0
16	13.82	7.3
20	14.12	9.6
24	14.39	11.7
28	14.69	14.1
32	15.11	17.3
36	14.14	17.4
40	15.52	20.5
44	16.11	25.1
48	16.30	26.6

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	600
Oil-in temp, °F	592
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1

TABLE 75. SUMMARY DATA ON F-1041, BEARING TEST NO. 28

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	12	2	24
Heater Mount (F)	57	3	171
Heater Mount (R)	40.5	3	121.5
Seal Plate	6	1	6
Test Bearing	36	5	180
			502.5

Overall Rating: 502.5/6 = 83.8

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil Consumption rate: 59 ml/hr

Total accumulated filter wt: Pressure 0.8 g Scavenge 0.8 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.07	1.5
8	13.37	3.8
12	13.44	4.3
16	13.78	7.0
20	13.91	8.0
24	14.22	10.4
28	14.46	12.3
32	14.73	14.4
36	14.99	16.4
40	15.33	19.0
44	15.59	21.0
48	15.95	23.8

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	600
Oil-in temp, °F	588
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 76. SUMMARY DATA ON F-1041, BEARING TEST NO. 30

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	15	2	30
Heater Mount (F)	17.5	3	52.5
Heater Mount (R)	18	3	54
Seal Plate	12	1	12
Test Bearing	39.1	5	195.5
			344

Overall Rating: 344/6 = 57.3

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 92 ml/hr

Total accumulated filter wt: Pressure 1.2 g Scavenge 0.6 g

Test Oil Performance*

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.30	3.3
8	13.96	8.4
12	14.64	13.7
16	15.58	21.0
20	15.79	22.6
24	17.66	37.1
28	19.02	47.7
32	21.37	65.9
36	22.65	75.9
40	24.70	91.8
41	26.19	103.3

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	650
Oil-in temp, °F	643
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil flow, ml/min 1200

TABLE 77. SUMMARY DATA ON F-1041, BEARING TEST NO. 31

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	9	2	18
Heater Mount (F)	52	3	156
Heater Mount (R)	28	3	84
Seal Plate	2.5	1	2.5
Test Bearing	37.6	5	188
			448.5

Overall Rating: 448.5/6 = 74.8

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 27 ml/hr

Total accumulated filter wt: Pressure 0.9 g Scavenge 0.5 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	12.98	0.8
8	13.07	1.5
12	13.16	2.2
16	13.26	3.0
20	13.30	3.3
24	13.44	4.3
28	13.45	4.4
32	13.54	5.1
36	13.60	5.6
40	13.72	6.5
44	13.79	7.1
48	13.93	8.2

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5-metal specimens in test oil sump	
Sump temp, °F	500
Oil-in temp, °F	492
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 78. SUMMARY DATA ON F-1041, BEARING TEST NO. 32

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	36	2	72
Heater Mount (F)	36	3	108
Heater Mount (R)	40.5	3	121.5
Seal Plate	0	1	0
Test Bearing	44.6	5	223
			524.5

Overall Rating: 524.5/6 = 87.4

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 195 ml/hr

Total accumulated filter wt: Pressure 0.5 g Scavenge 0.5 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.24	2.8
8	13.98	8.5
12	14.75	14.5
16	15.65	21.5
20	15.65	21.5
24	17.31	34.4
28	19.28	49.7
32*	20.96	62.7
36	13.78	7.0
40	14.91	15.8
44	16.30	26.6
48	17.33	34.5

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	650
Oil-in temp, °F	635
Bearing temp, °F	700
Air flow to bearing m chine, cfm	0.35
Air flow to test oil sump, cfm	0.5

*Oil changed at 32 hr through error

TABLE 79. SUMMARY DATA ON F-1041, BEARING TEST NO. 34

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	6	1	6
Spacer and Nut	6	2	12
Heater Mount (F)	26	3	78
Heater Mount (R)	17.5	3	52.5
Seal Plate	0	1	0
Test Bearing	31.1	5	155.5
			304

Overall Rating: 304/6 = 50.7

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 132 ml/hr

Total accumulated filter wt: Pressure 0.6 g Scavenge 0.5 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.13	1.9
8	13.84	7.5
12	14.40	11.8
16	15.21	18.1
20	15.84	23.0
24	17.20	33.5
28	18.33	42.3
32	20.08	55.9
36	20.48	59.0
40	21.88	69.9
44	27.12	111.0

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5 metal specimens in test oil sump	
Sump temp, °F	650
Oil-in temp, °F	638
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0.25

TABLE 80. SUMMARY DATA ON F-1041, BEARING TEST NO. 35

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	3	1	3
Spacer and Nut	30	2	60
Heater Mount (F)	22.5	3	67.5
Heater Mount (R)	24.5	3	73.5
Seal Plate	0	1	0
Test Bearing	36	5	180
			384

Overall Rating: 384/6 = 64

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 138 ml/hr

Total accumulated filter wt: Pressure 0.8 g Scavenge 0.5 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.23	2.7
8	13.72	6.5
12	14.62	13.5
16	15.26	18.5
20	15.76	22.4
24	17.02	32.1
28	17.96	39.4
32	19.53	51.6
36	20.40	58.4
40	22.42	74.1
44	25.11	95.0
48	26.19	103.0

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	650
Oil-in temp, °F	633
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 81. SUMMARY DATA ON F-1041, BEARING TEST NO. 36

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	3	2	6
Heater Mount (F)	30	3	90
Heater Mount (R)	29	3	87
Seal Plate	0	1	0
Test Bearing	33.1	5	165.5
			348.5

Overall Rating: 348.5/6 = 58.1

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 127 ml/hr

Total accumulated filter wt: Pressure 0.7 g Scavenge 0.4 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	13.10	1.7
8	13.69	6.3
12	14.29	10.9
16	15.03	16.7
20	15.59	21.0
24	16.97	31.8
28	17.77	38.0
32	19.16	48.8
36	19.73	53.2
40	22.53	74.9
44	25.03	94.3
48	27.07	110.2

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	650
Oil-in temp, °F	640
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 82. SUMMARY DATA ON F-1041, BEARING TEST NO. 38

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	42	2	84
Heater Mount (F)	37.5	3	112.5
Heater Mount (R)	29	3	87
Seal Plate	0	1	0
Test Bearing	39.1	5	195
			478.5

Overall Rating: 478.5/6 = 79.8

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 117 ml/hr
Total accumulated filter wt: Pressure 1.6 g Scavenge 1.9 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F
0	12.88	--
4	12.98	0.1
8	13.50	4.8
12	14.13	9.7
16	14.36	11.5
20	14.74	14.4
24	15.16	17.7
28	15.63	21.4
32	16.16	25.5
36	16.49	28.0
40	17.00	32.0
44	17.94	39.3
48	18.49	43.6

Neutralization No.: 0.0 mg KOH/g for all samples

Rig No 2, with 5 metal specimens in test oil sump

Sump temp, °F	650
Oil-in temp, °F	636
Bearing temp, °F	700
Air flow to bearing machine, cfm	0 35
Air flow to test oil sump, cfm	0

TABLE 83. SUMMARY DATA ON O-62-25, BEARING TEST NO. 47

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	3	1	3
Spacer and Nut	9	2	18
Heater Mount (F)	44	3	132
Heater Mount (R)	17	3	51
Seal Plate	3	1	3
Test Bearing	18.4	5	92
			299

Overall Rating: 299/6 = 49.8

Not included in official rating: Sump - wall 100% L sludge
bottom 100% M sludge

Oil consumption rate: 67 ml/hr

Total accumulated filter wt: Pressure 1.5 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	15.59	--	3.52	0.05
4	16.19	3.8	3.60	0.07
8	16.51	5.9	3.66	0.21
12	16.97	8.9	3.73	0.35
16	17.22	10.5	3.77	0.43
20	17.39	11.5	3.80	0.72
24	17.88	14.7	3.83	0.40
28	17.94	15.1	3.86	0.31
32	18.30	17.4	3.92	1.03
36	18.30	17.4	3.92	1.21
40	18.73	20.1	3.98	1.23
44	19.22	23.3	4.05	1.05
48	19.80	27.0	4.13	1.86

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	415
Bearing temp, °F	475
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 84. SUMMARY DATA ON O-62-25, BEARING TEST NO. 48

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	3	1	3
Spacer and Nut	30	2	60
Heater Mount (F)	46	3	138
Heater Mount (R)	35	3	105
Seal Plate	10	1	10
Test Bearing	18.5	5	92.5
			408.5

Overall Rating: 408.5/6 = 68.1

Not included in official rating: Sump - wall 100% M sludge
bottom 100% M sludge

Oil consumption rate: 74 ml/hr

Total accumulated filter wt: Pressure 1.4 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	15.59	--	3.52	0.05
4	16.23	4.1	3.60	0.05
8	16.59	6.4	3.67	0.14
12	17.15	10.0	3.73	0.28
16	17.21	10.4	3.77	0.37
20	17.50	12.3	3.85	0.52
24	17.79	14.1	3.86	0.60
28	18.16	16.5	3.88	0.63
32	18.38	17.9	3.94	0.94
36	18.86	21.0	4.02	1.36
40	20.07	28.7	4.17	2.06
44	20.56	31.9	4.24	2.18
48	20.73	33.0	4.27	2.28

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	415
Bearing temp, °F	475
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 85. SUMMARY DATA ON O-62-25, BEARING TEST NO. 49

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	3	1	3
Spacer and Nut	10	2	20
Heater Mount (F)	13	3	39
Heater Mount (R)	20.5	3	61.5
Seal Plate	0	1	0
Test Bearing	19.2	5	96
			219.5

Overall Rating: 219.5/6 = 36.6

Not included in official rating: Sump - wall 100% M sludge
bottom 100% M sludge

Oil consumption rate: 85 ml/hr

Total accumulated filter wt: Pressure 2.0 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	15.59	--	3.52	0.05
4	16.11	3.3	3.58	0.05
8	16.63	6.7	3.68	0.20
12	17.06	9.4	3.74	0.37
16	17.18	10.2	3.76	0.54
20	17.68	13.4	3.84	0.61
24	18.10	16.1	3.90	0.83
28	18.33	17.6	3.92	0.86
32	18.68	19.8	3.97	1.02
36	18.88	21.1	4.00	1.05
40	19.77	26.8	4.16	1.75
44	20.30	30.2	4.19	2.03
48	20.75	33.1	4.26	2.03

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	418
Bearing temp, °F	475
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 86. SUMMARY DATA ON O-62-25, BEARING TEST NO. 50

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	3	1	3
Spacer and Nut	12	2	24
Heater Mount (F)	25.5	3	76.5
Heater Mount (R)	10	3	30
Seal Plate	3	1	3
Test Bearing	12.5	5	62.5
			199

Overall Rating: 199/6 = 33.2

Not included in official rating: Sump - wall 100% M varnish
bottom 100% M varnish

Oil consumption rate: 76 ml/hr

Total accumulated filter wt: Pressure 1.4 g Scavenge 1.3 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	15.59	--	3.52	0.04
4	16.13	3.5	3.59	0.04
8	16.26	4.3	3.67	0.17
12	16.89	8.3	3.71	0.30
16	17.07	9.5	3.76	0.40
20	17.20	10.3	3.79	0.44
24	17.57	12.7	3.83	0.56
28	17.92	14.9	3.87	0.63
32	18.25	17.1	3.92	0.76
36	18.50	18.7	3.95	0.84
40	18.96	21.6	4.03	1.30
44	19.73	26.6	4.12	1.66
48	20.11	29.0	4.17	1.96

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	415
Bearing temp, °F	475
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 87. SUMMARY DATA ON O-62-25, BEARING TEST NO. 45

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	3	1	3
Spacer and Nut	63	2	126
Heater Mount (F)	79	3	237
Heater Mount (R)	35	3	105
Seal Plate	4	1	4
Test Bearing	49.7	5	248.5
			723.5

Overall Rating: 723.5/6 = 120.6

Not included in official rating: Sump - wall 100% M sludge;
bottom 100% M sludge

Oil consumption rate: 93 ml/hr

Total accumulated filter wt: Pressure 1.2 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	15.59	--	3.52	0.04
4	16.18	3.8	3.60	0.06
8	16.54	6.1	3.72	0.26
12	17.62	13.0	3.85	0.56
16	18.70	19.9	4.00	1.03
20	20.09	28.9	4.18	1.28
24	20.85	33.7	4.29	1.62
28	21.76	39.6	4.43	1.99
32	22.97	47.3	4.58	2.13
36	23.39	50.0	4.68	2.65
40	24.66	58.2	4.83	2.81
44	26.63	70.8	5.12	3.23
48	26.54	70.2	5.12	3.39

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	416
Bearing temp, °F	500
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 88. SUMMARY DATA ON O-62-25, BEARING TEST NO. 46

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	3	1	3
Spacer and Nut	12.5	2	25
Heater Mount (F)	25.5	3	76.5
Heater Mount (R)	8.5	3	25.5
Seal Plate	1	1	1
Test Bearing	16	5	80
			211

Overall Rating: 211/6 = 35.2

Not included in official rating: Sump - wall 100% M sludge
bottom 100% H sludge

Oil consumption rate: 130 ml/hr

Total accumulated filter wt: Pressure 2.1 g Scavenge 0.9 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	15.59	--	3.52	0.04
4	16.47	5.6	3.65	0.14
8	17.24	10.6	3.77	0.50
12	18.24	17.0	3.91	0.83
16	19.47	24.9	4.09	1.39
20	20.36	30.6	4.23	1.84
24	22.52	44.5	4.46	2.41
28	22.74	45.9	4.53	2.41
32	23.91	53.4	4.69	2.79
36	24.82	59.2	4.85	3.01
40	26.32	68.8	5.05	3.34
44	27.74	77.9	5.22	3.55
48	26.97	73.0	5.12	3.41

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	450
Oil-in temp, °F	438
Bearing temp, °F	475
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 89. SUMMARY DATA ON H-1001, BEARING TEST NO. 76

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	12	1	12
Spacer and Nut	38	2	76
Heater Mount (F)	81.5	3	244.5
Heater Mount (R)	53.5	3	160.5
Seal Plate	9	1	9
Test Bearing	23.8	5	119
			621

Overall Rating: 621/6 = 103.5

Not included in official rating: Sump - wall 100% clean
bottom 30% L sludge, 70% clean

Oil consumption rate: 96 ml/hr

Total accumulated filter wt: Pressure 1.4 g Scavenge 1.6 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	-	5.08	0.09
4	28.84	4.9	5.21	0.27
8	30.46	10.8	5.48	0.43
12	31.45	14.4	5.48	0.74
16	32.51	18.2	5.60	0.82
20	32.70	18.9	5.66	1.01
24	34.36	24.9	5.82	1.25
28	35.83	30.3	5.94	1.63
32	37.24	35.4	6.15	1.94
36	37.40	36.0	6.20	2.18
40	39.67	44.3	6.41	2.69
44	43.72	59.0	6.80	3.69
48	48.49	76.3	7.28	4.34

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	416
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1.0

TABLE 90. SUMMARY DATA ON H-1001, BEARING TEST NO. 66

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	20	2	40
Heater Mount (F)	45.5	3	136.5
Heater Mount (R)	59.5	3	178.5
Seal Plate	0	1	0
Test Bearing	23.5	5	117.5
			472.5

Overall Rating: 472.5/6 = 78.8

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 55 ml/hr
Total accumulated filter wt: Pressure 0.8 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	28.88	5.0	5.20	0.18
8	30.41	10.6	5.45	0.32
12	31.09	13.1	5.47	0.45
16	32.22	17.2	5.59	0.54
20	32.60	18.5	5.63	0.70
24	33.42	21.5	5.74	0.76
28	34.22	24.4	5.84	0.96
32	35.01	27.3	5.91	1.03
36	35.77	30.1	6.01	1.23
40	36.22	31.7	6.05	1.28
44	37.08	34.8	6.13	1.44
48	39.09	42.1	6.35	1.86

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	417
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 91. SUMMARY DATA ON H-1001, BEARING TEST NO. 72

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	37.5	2	75
Heater Mount (F)	54	3	162
Heater Mount (R)	61	3	183
Seal Plate	0	1	0
Test Bearing	25.5	5	127.5
			547.5

Overall Rating: 547.5/6 = 91.3

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 50 ml/hr

Total accumulated filter wt: Pressure 0.9 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	29.13	5.9	5.23	0.21
8	30.68	11.6	5.42	0.37
12	31.08	13.0	5.50	0.49
16	32.06	16.6	5.68	0.70
20	33.09	20.3	5.71	0.86
24	33.75	22.7	5.84	1.01
28	35.15	27.8	5.96	1.05
32	36.23	31.7	6.08	1.35
36	37.42	36.1	6.19	1.45
40	39.55	43.8	6.44	1.68
44	41.24	50.0	6.64	1.93
48	45.18	64.3	7.06	2.18

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	416
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 92. SUMMARY DATA ON H-1001, BEARING TEST NO. 51

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	3	1	3
Spacer and Nut	14.5	2	29
Heater Mount (F)	20	3	60
Heater Mount (R)	19.5	3	58.5
Seal Plate	0	1	0
Test Bearing	12.5	5	62.5
			213

Overall Rating: 213/6 = 35.5

Not included in official rating: Sump - wall 100% L varnish
bottom 100% L sludge

Oil consumption rate: 53 ml/hr

Total accumulated filter wt: Pressure 0.8 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	29.18	6.1	5.25	0.21
8	30.59	11.2	5.45	0.36
12	31.27	13.7	5.51	0.53
16	33.02	20.1	5.69	0.73
20	33.87	23.2	5.80	1.02
24	35.25	28.2	5.97	1.28
28	35.94	30.7	6.05	1.48
32	38.83	41.2	6.35	1.97
36	39.92	45.2	6.47	1.90
40	42.44	54.3	6.72	2.20
44	44.86	63.1	6.93	2.56
48	46.79	70.1	7.17	2.66

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	450
Oil-in temp, °F	440
Bearing temp, °F	500
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 93. SUMMARY DATA ON H-1001, BEARING TEST NO. 52

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	12.5	2	25
Heater Mount (F)	15	3	45
Heater Mount (R)	16	3	48
Seal Plate	6.5	1	6.5
Test Bearing	13.6	5	68
			192.5

Overall Rating: 192.5/6 = 32.1

Not included in official rating: Sump - wall 100% L varnish
bottom 100% L varnish

Oil consumption rate: 116 ml/hr

Total accumulated filter wt: Pressure 1.0 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.08
4	30.22	9.8	5.40	0.31
8	33.10	20.4	5.69	0.72
12	35.76	30.0	6.03	1.26
16	40.20	46.2	6.47	1.57
20	42.84	55.8	6.78	1.60
24	46.99	70.9	7.19	2.11
28	49.76	80.9	7.54	2.22
32*	54.69	98.9	8.10	2.63
36	31.67	15.2	5.54	0.47
40	34.26	24.6	5.89	0.89
44	37.47	36.3	6.12	1.35
48	40.71	48.0	6.53	1.46

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	475
Oil-in temp, °F	464
Bearing temp, °F	525
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 32 hr due to viscosity increase.

TABLE 94. SUMMARY DATA ON H-1001, BEARING TEST NO. 53

Demerit Ratings

Item	Rating	Factor	Demerit
End Cover	0	1	0
Spacer and Nut	10	2	20
Heater Mount (F)	22	3	66
Heater Mount (R)	22	3	66
Seal Plate	10	1	10
Test Bearing	14.1	5	70.5
			232.5

Overall Rating: 232.5/6 = 38.8

Not included in official rating: Sump - wall 5% H varnish, 95% L varnish
bottom 100% L varnish

Oil consumption rate: 121 ml/hr

Total accumulated filter wt: Pressure 1.0 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	31.10	13.1	5.46	0.39
8	35.34	28.5	5.95	1.02
12	39.77	44.6	6.48	1.35
16	46.60	69.4	7.13	1.95
20	50.96	85.3	7.65	2.31
24*	28.38	3.2	5.16	0.31
28	33.95	23.4	5.78	0.57
32	38.50	40.0	6.31	1.16
36	43.27	57.3	6.85	1.49
40	49.37	79.5	7.59	1.53
44**	56.30	104.7	8.15	1.77

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	500
Oil-in temp, °F	487
Bearing temp, °F	550
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 23.5 hr due to viscosity increase.

**Test terminated at 44 hr due to viscosity increase.

TABLE 95. SUMMARY DATA ON H-1001, BEARING TEST NO. 54

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	10	2	20
Heater Mount (F)	33	3	99
Heater Mount (R)	32	3	96
Seal Plate	0	1	0
Test Bearing	18.5	5	92.5
			307.5

Overall Rating: 307.5/6 = 51.3

Not included in official rating: Sump - wall 20% M varnish, 80% L varnish
bottom 100% L varnish

Oil consumption rate: 148 ml/hr

Total accumulated filter wt: Pressure 1.1 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	31.17	13.3	5.48	0.30
8	36.03	31.0	6.01	0.90
12	42.84	55.8	6.81	1.23
16	50.08	82.1	7.53	1.46
20	51.68	87.9	7.82	1.63
24*	31.57	14.8	5.55	0.36
28	37.94	38.0	6.30	0.71
32	44.84	63.1	7.00	1.12
36	47.18	71.6	7.32	1.34
40*	54.65	98.7	8.04	1.57
44	34.44	25.2	5.83	0.57
48	40.71	48.0	6.56	0.97

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	513
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 21.5 and 40 hr due to viscosity increase.

TABLE 96. SUMMARY DATA ON H-1001, BEARING TEST NO. 59

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	16.5	2	33
Heater Mount (F)	42	3	126
Heater Mount (R)	34	3	102
Seal Plate	0	1	0
Test Bearing	22	5	110
			371

Overall Rating: 371/6 = 61.8

Not included in official rating: Sump - wall 10% H varnish, 90% L varnish
bottom 100% L varnish

Oil consumption rate: 207 ml/hr

Total accumulated filter wt: Pressure 1.0 g Scavenge 1.2 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	31.50	14.5	5.11	0.53
8	40.64	47.8	6.48	1.38
12	50.57	83.9	7.52	2.13
16*	63.15	129.6	8.79	2.35
20	34.34	24.9	5.83	1.01
24	43.78	59.2	6.84	1.41
28*	54.93	99.7	7.98	2.01
32	35.07	27.5	5.89	0.61
36	42.17	53.3	6.67	1.23
40	51.40	86.9	7.62	1.51
43**	56.18	104.3	8.19	1.67

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	511
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 16 and 28 hr due to viscosity increase.

**Test terminated at 43 hr due to viscosity increase.

TABLE 97. SUMMARY DATA ON H-1001, BEARING TEST NO. 60

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	36	2	72
Heater Mount (F)	42	3	126
Heater Mount (R)	40	3	120
Seal Plate	0	1	0
Test Bearing	32	5	160
			478

Overall Rating: 478/6 = 79.7

Not included in official rating: Sump - **wall 10% L varnish, 90% clean**
bottom 100% clean

Oil consumption rate: 213 ml/hr

Total accumulated filter wt: Pressure 1.0 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	31.58	14.8	5.51	0.27
8	38.19	38.9	6.27	0.65
12	44.52	61.9	6.97	0.98
16*	53.23	93.6	7.86	1.27
20	33.23	20.8	5.70	0.46
24	39.32	43.0	6.40	0.76
28	44.81	62.9	6.99	1.08
32*	52.58	91.2	7.85	1.23
36	33.17	20.6	5.67	0.31
40	39.40	43.3	6.45	0.83
44	45.74	66.3	7.10	1.10
48	51.84	88.5	7.72	1.19

Rig No. 1 with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	514
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 16 and 32 hr due to viscosity increase.

TABLE 98. SUMMARY DATA ON H-1001, BEARING TEST NO. 61

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	17	2	34
Heater Mount (F)	22.5	3	67.5
Heater Mount (R)	28	3	84
Seal Plate	0	1	0
Test Bearing	19.3	5	96.5
			282

Overall Rating: 282/6 = 47

Not included in official rating: Sump - **wall 30% H varnish, 70% clean**
bottom 100% clean

Oil consumption rate: 202 ml/hr
Total accumulated filter wt: Pressure 1.0 g Scavenge 1.2 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	30.93	12.5	5.35	0.33
8	37.06	34.8	6.15	0.63
12	42.33	53.9	6.73	1.04
16	48.93	77.9	7.45	1.32
20*	52.98	92.7	7.83	1.35
24	32.76	19.1	5.66	0.59
28	39.41	43.3	6.55	1.12
32	45.74	66.3	7.11	1.26
36	50.00	81.8	7.57	1.37
40	28.95	5.3	5.23	0.16
44	36.58	33.0	6.07	0.70
48	42.95	56.2	6.77	1.12

Heater difficulties resulted in a test bearing temp of 560°F for first 16 hr operation, thereby invalidating this test.

Rig No. 1, with 5-metal specimens in test oil sump	
Sump temp, °F	525
Oil-in temp, °F	513
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 21 and 39 hr due to viscosity increase.

TABLE 99. SUMMARY DATA ON H-1001, BEARING TEST NO. 62

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	12	2	24
Heater Mount (F)	20.5	3	61.5
Heater Mount (R)	62	3	186
Seal Plate	0	1	0
Test Bearing	16.8	5	84
			355.5

Overall Rating: 355.5/6 = 59.3

Not included in official rating: Sump-wall 40% H varnish, 10% L varnish 50% clean; bottom 100% clean

Oil consumption rate: 197 ml/hr
Total accumulated filter wt: Pressure 1.0 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	31.45	14.4	5.52	0.29
8	37.52	36.4	6.21	0.83
12	41.87	52.3	6.68	1.05
16	49.13	78.7	7.46	1.23
20*	28.52	3.7	5.15	0.17
24	35.32	28.4	5.96	0.42
28	41.24	50.0	6.58	0.52
32	47.23	71.7	7.24	0.79
36	49.97	81.7	7.83	1.04
40*	30.31	10.2	5.36	0.17
44	37.08	34.8	6.09	0.86
48	43.01	56.4	6.77	1.04

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	513
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 19.5 and 38.5 hr due to viscosity increase.

TABLE 100. SUMMARY DATA ON H-1001, BEARING TEST NO. 63

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	15	2	30
Heater Mount (F)	25	3	75
Heater Mount (R)	46.5	3	139.5
Seal Plate	0	1	0
Test Bearing	20.8	5	104
			348.5

Overall Rating: 348.5/6 = 58.1

Not included in official rating: Sump - wall 100% L varnish
bottom 100% clean

Oil consumption rate: 210 ml/hr

Total accumulated filter wt: Pressure 0.9 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	31.17	13.3	5.47	0.22
8	36.77	33.7	6.11	0.57
12	42.54	54.7	6.77	0.79
16	50.11	82.2	7.61	1.02
20*	28.03	1.9	5.68	0.07
24	35.23	28.1	5.88	0.36
28	41.43	50.7	6.64	0.73
32	48.14	75.1	7.34	0.75
36*	52.12	89.5	7.76	0.95
40	32.79	19.2	5.70	0.27
44	38.51	40.0	6.26	0.64
48	44.78	62.8	7.10	0.80

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	513
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 19.5 and 37 hr due to viscosity increase.

TABLE 101. SUMMARY DATA ON H-1001, BEARING TEST NO. 64

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	17	2	34
Heater Mount (F)	26.5	3	79.5
Heater Mount (R)	53.5	3	160.5
Seal Plate	0	1	0
Test Bearing	24.5	5	122.5
			396.5

Overall Rating: 396.5/6 = 66.1

Not included in official rating: Sump - **wall 35% H varnish, 65% clean**
bottom 100% clean

Oil consumption rate: 227 ml/hr

Total accumulated filter wt: Pressure 0.9 g Scavenge 1.2 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	32.78	19.2	5.61	0.59
8	41.75	51.8	6.63	1.13
12*	51.19	86.1	7.62	1.56
16	31.87	15.9	5.54	0.50
20	38.35	39.5	6.27	0.99
24	48.18	75.2	7.31	1.62
28*	31.09	13.1	5.47	0.30
32	40.48	47.2	6.59	1.26
36	45.26	64.6	7.02	1.45
40*	29.16	6.0	5.23	0.13
44	38.67	40.6	6.32	0.89
48	46.82	70.3	7.22	1.32

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	512
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 14, 26.5, and 39.5 hr due to viscosity increase.

TABLE 102. SUMMARY DATA ON H-1001, BEARING TEST NO. 65

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	15.5	2	31
Heater Mount (F)	28	3	84
Heater Mount (R)	48	3	144
Seal Plate	0	1	0
Test Bearing	28.8	5	144
			403

Overal Rating: 403/6 = 67.2

Not included in official rating: Sump - wall 20% H varnish, 30% L smooth carbon; 50% clean; bottom 100% clean

Oil consumption rate: 323 ml/hr

Total accumulated filter wt: Pressure 0.9 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	34.47	25.3	5.81	0.80
8*	53.84	95.8	7.80	2.28
12	34.50	25.5	5.84	0.62
16*	54.52	98.3	7.87	2.28
20	42.59	54.9	6.68	1.85
24*	33.86	23.1	5.76	0.62
28*	28.27	28.0	5.16	0.21
32*	50.21	82.6	7.45	2.49
36	36.83	33.9	6.08	1.07
40*	30.34	10.3	5.40	0.26
44**	54.74	99.1	7.85	2.57

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	512
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1

*Test oil changed at 10, 16, 22.5, 27.5, 33.5 and 39 hr due to viscosity increase.

**Test terminated at 43.75 hr due to viscosity increase.

TABLE 103. SUMMARY DATA ON H-1001, BEARING TEST NO. 55

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	10	1	10
Spacer and Nut	30	2	60
Heater Mount (F)	68	3	204
Heater Mount (R)	69	3	207
Seal Plate	0	1	0
Test Bearing	26.4	5	132
			613

Overall Rating: 613/6 = 102.2

Not included in official rating: Sump - wall 75% H varnish, 25% clean
bottom 100% L varnish

Oil consumption rate: 254 ml/hr

Total accumulated filter wt: Pressure 1.1 g Scavenge 0.9 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.50	--	5.08	0.07
4	32.65	18.7	5.63	0.54
8	41.69	51.6	6.66	1.45
12*	55.97	103.5	8.08	1.49
16	36.60	33.1	6.22	0.82
20	45.11	64.0	7.00	1.03
24*	30.04	9.2	5.33	0.16
28	41.45	50.7	6.63	0.88
32*	54.70	98.9	8.02	1.42
36	35.83	30.3	6.00	0.57
40	47.99	74.5	7.32	1.16
42.5**	52.65	91.5	7.81	1.49

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	550
Oil-in temp, °F	535
Bearing temp, °F	600
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 12, 23, and 32 hr due to viscosity increase.

**Test terminated at 42.5 hr due to viscosity increase.

TABLE 104. SUMMARY DATA ON O-64-13, BEARING TEST NO. 77

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	4	1	4
Spacer and Nut	60	2	120
Heater Mount (F)	67.5	3	202.5
Heater Mount (R)	48.5	3	145.5
Seal Plate	12.5	1	12.5
Test Bearing	45.6	5	228
			712.5

Overall Rating: 712.5/6 = 118.8

Not included in official rating: Sump - wall 100% M sludge
bottom 50% M sludge, 50% clean

Oil consumption rate: 114 ml/hr

Total accumulated filter wt: Pressure 0.7 g Scavenge 0.8 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	28.43	-	5.32	0.28
4	29.36	3.3	5.45	0.35
8	31.00	9.0	5.54	0.49
12	32.58	14.6	5.82	0.67
16	37.07	30.4	6.37	1.47
20	38.44	35.2	6.54	1.85
24	43.17	51.8	7.33	2.73
28	47.92	68.6	7.60	3.33
32*	52.18	83.5	7.88	3.50

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil in temp, °F	414
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

* Test was terminated at 32 hr due to excessive deposit formation

TABLE 105. SUMMARY DATA ON O-64-13, BEARING TEST NO. 79

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	24.5	1	24.5
Spacer and Nut	57	2	114
Heater Mount (F)	93.5	3	280.5
Heater Mount (R)	95.5	3	286.5
Seal Plate	8	1	8
Test Bearing	41.6	5	208
			921.5

Overall Rating: 921.5/6 = 153.6

Not included in official rating: Sump - wall 75% L sludge, 25% L varnish
bottom 100% L sludge

Oil consumption rate: 111 ml/hr

Total accumulated filter wt: Pressure 1.0 g Scavenge 1.6 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	28.43	--	5.32	0.28
4	29.38	3.3	5.45	0.27
8	30.75	8.2	5.64	0.33
12	33.75	18.7	5.96	0.82
16*	33.15	16.6	5.92	0.71
20	34.03	19.7	6.02	0.94
24	36.63	28.8	6.30	1.63
28	39.20	37.9	6.57	2.21
32	43.72	53.8	7.03	2.98
36	46.91	65.0	7.41	3.53
40	50.83	78.8	7.81	3.59
44	54.06	90.2	8.13	3.98
48	57.02	101	8.46	4.04

Rig No. 2 with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil in temp, °F	416
Bearing temp, °F	525
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

* At 13.3 hr a broken pressure line caused a test oil loss of approximately 3000 ml.

TABLE 106. SUMMARY DATA ON O-64-13, BEARING TEST NO. 80

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	26	1	26
Spacer and Nut	51.5	2	103
Heater Mount (F)	75	3	225
Heater Mount (R)	58.5	3	175.5
Seal Plate	0	1	0
Test Bearing	56.6	5	283
			812.5

Overall Rating: 812.5/6 = 135.4

Not included in official rating: Sump - wall 100% H varnish
bottom 100% clean

Oil consumption rate: 312 ml/hr

Total accumulated filter wt: Pressure 1.2 g Scavenge 1.3 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	28.43	--	5.32	0.28
4	32.27	13.5	5.81	0.37
8	42.02	47.8	6.94	0.72
12	50.98	79.3	7.91	1.04
16*	28.86	1.5	5.38	0.33
20	35.08	23.4	6.20	0.34
24	44.28	55.7	7.19	0.67
28*	54.31	91.0	8.31	0.85
32	33.85	19.1	6.01	0.34
36	39.74	39.8	6.67	0.47
40	51.00	79.4	7.93	0.89
43.5**	60.53	112.9	9.00	1.02

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil in temp, °F	513
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 15.5 and 29 hr due to viscosity increase.

**Test terminated at 43.5 hr due to viscosity increase.

TABLE 107. SUMMARY DATA ON O-64-17, BEARING TEST NO. 88

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	15.5	1	15.5
Spacer and Nut	67	2	134
Heater Mount (F)	49.5	3	148.5
Heater Mount (R)	65.5	3	196.5
Seal Plate	15	1	15
Test Bearing	36	5	180
			689.5

Overall Rating: 689.5/6 = 114.9

Not included in official rating: Sump - wall 80% L varnish, 20% L sludge
bottom 100% L varnish

Oil consumption rate: 62 ml/hr

Total accumulated filter wt: Pressure 1.2 g Scavenge 1.7 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	28.37	---	5.29	0.33
4	30.04	5.9	5.60	0.33
8	32.81	15.6	5.81	0.49
12	34.33	21.0	6.04	0.68
16	36.14	27.4	6.27	0.80
20	37.12	30.8	6.42	1.05
24	38.52	35.8	6.68	1.21
28	40.39	42.4	6.88	1.23
32	41.51	46.3	7.03	1.39
36	42.69	50.5	7.18	1.49
40	44.31	56.2	7.42	1.68
44	45.31	59.7	7.61	1.73
48	47.10	66.0	7.85	1.91

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil in temp, °F	415
Bearing temp, °F	525
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 108. SUMMARY DATA ON ATL-304, BEARING TEST NO. 39

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	10	1	10
Spacer and Nut	18	2	36
Heater Mount (F)	27	3	81
Heater Mount (R)	34	3	102
Seal Plate	0	1	0
Test Bearing	22.7	5	113.5
			342.5

Overall Rating: 324.5/6 = 57.1

Not included in official rating: Sump - wall 100% L varnish
bottom 100% L varnish

Oil consumption rate: 117 ml/hr

Total accumulated filter wt: Pressure 0.8 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut., No., mg KOH/g
0	47.11	-	8.18	0.12
4	50.29	6.8	8.42	0.83
8	62.54	32.9	9.63	1.59
12	75.81	60.9	11.11	2.11
16*	90.62	92.4	12.66	2.29
20	52.45	11.3	8.68	0.83
24	68.34	45.1	10.12	1.60
28	76.99	63.4	11.18	1.75
32*	96.12	104	13.06	2.22
36	56.21	19.3	9.03	0.99
40	65.49	39.0	9.97	1.50
44	84.66	79.7	11.92	2.22
48	104.4	122	13.30	2.58

Rig. No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	500
Oil-in temp, °F	493
Bearing temp, °F	550
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 16 and 32 hr due to viscosity increase

TABLE 109. SUMMARY DATA ON ATL-305, BEARING TEST NO. 44

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	0	2	0
Heater Mount (F)	44.5	3	133.5
Heater Mount (R)	70.5	3	211.5
Seal Plate	0	1	0
Test Bearing	14.2	5	71
			416

Overall Rating: 416/6 = 69.3

Not included in official rating: Sump - wall 100% L varnish
bottom 100% L varnish

Oil consumption rate: 138 ml/hr

Total accumulated filter wt: Pressure 1.0 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.16	--	5.10	0.10
4	29.07	11.1	5.53	0.48
8	36.00	37.6	6.30	1.12
12	41.06	57.0	6.87	1.43
16	46.62	78.2	7.54	1.75
20*	48.01	83.5	7.99	1.68
24	31.11	18.9	5.76	0.71
28	36.02	37.7	6.49	1.19
32	41.38	58.2	7.01	1.34
36	47.94	83.3	7.79	1.91
40*	51.84	98.2	8.28	1.86
44	31.19	19.2	5.89	0.79
48	38.98	49.0	6.74	1.24

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	475
Oil-in temp, °F	465
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

* Test oil changed at 21 and 40 hr due to viscosity increase

TABLE 110. SUMMARY DATA ON ATL-305, BEARING TEST NO. 43

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	25.5	2	51
Heater Mount (F)	108	3	324
Heater Mount (R)	89	3	267
Seal Plate	0	1	0
Test Bearing	22.4	5	112
			754

Overall Rating: 754/6 = 125.7

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 118 ml/hr

Total accumulated filter wt: Pressure 0.8 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.16	--	5.10	0.10
4	29.21	11.7	5.51	0.42
8	35.40	35.2	6.30	0.96
12	38.33	46.5	6.62	1.27
16	44.71	70.9	7.38	1.70
20	47.93	83.2	7.84	1.80
24*	27.15	3.8	5.24	0.21
28	33.69	28.8	6.06	0.79
32	39.89	52.5	6.77	1.31
36	45.37	78.3	7.43	1.82
40	47.71	82.3	7.79	1.92
44	50.14	91.7	8.07	2.04
47	55.03	103.6	8.61	2.27

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	475
Oil-in temp, °F	465
Bearing temp, °F	625
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 23.3 hr due to viscosity increase

TABLE 111. SUMMARY DATA ON ATL-305, BEARING TEST NO. 42

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	6	2	12
Heater Mount (F)	4	3	12
Heater Mount (R)	16.5	3	49.5
Seal Plate	6	1	6
Test Bearing	5.9	5	29.5
			109

Overall Rating. 109/6 = 18.2

Not included in official rating: Sump - wall 5% L varnish, 95% clean
bottom 100% clean

Oil consumption rate: 161 ml/hr
Total accumulated filter wt: Pressure 0.5 g Scavenge 0.6 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.16	-	5.10	0.10
4	29.44	12.5	5.51	0.96
8	38.36	46.6	6.63	1.19
12*	52.74	101.6	8.36	1.48
16	33.93	29.7	6.11	1.21
20	39.44	50.8	6.78	1.26
24	47.21	80.5	(Sample lost in handling)	
28*	27.64	5.7	5.36	0.35
32	35.85	37.0	6.40	0.98
36	41.41	58.3	7.04	1.42
40*	27.04	3.4	5.26	0.19
44	34.52	32.0	6.27	1.17
48	43.17	65.0	7.33	1.43

Rig No. 1, with 5 metal specimens in test oil sump

Sump temp, °F	500
Oil-in temp, °F	493
Bearing temp, °F	550
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 12, 27, and 40 hr due to viscosity increase

TABLE 112. SUMMARY DATA ON ATL-307, BEARING TEST NO. 41

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	18	1	18
Spacer and Nut	85.5	2	171
Heater Mount (F)	57	3	171
Heater Mount (R)	12	3	36
Seal Plate	48	1	48
Test Bearing	45.4	5	227
			671

Overall Rating: 671/6 = 111.8

Not included in official rating: Sump - wall 100% L sludge
bottom 100% L sludge

Oil consumption rate: 15 ml/hr

Total accumulated filter wt: Pressure 2.6 g Scavenge 1.5 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F	Vis, cs at 100°F
0	25.69	--	286.9
4	26.01	2.6	296.0
8	26.47	2.9	303.8
12	26.71	3.8	306.6
16	26.82	4.2	308.2
20	26.67	3.7	308.3
24	26.78	4.1	310.6
28	26.94	4.9	312.6
32	27.01	5.1	312.4
36	27.14	5.6	311.3
40	27.18	5.8	313.4
44	27.14	5.6	314.2
48	27.31	6.3	313.9

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	500
Oil-in temp, °F	489
Bearing temp, °F	588*
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cmf	0

*Test bearing held at this temperature average without application of external heat.

TABLE 113. SUMMARY DATA ON ATL-307, BEARING TEST NO. 40

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	27	1	27
Spacer and Nut	56.5	2	113
Heater Mount (F)	99.5	3	298.5
Heater Mount (R)	94.5	3	283.5
Seal Plate	9	1	9
Test Bearing	550	5	2750
			3481

Overall Rating: 3481/6 = 580.2

Not included in official rating: Sump - wall 100% L flaked carbon
bottom 100% L flaked carbon

Oil consumption rate: 148 ml/hr

Total accumulated filter wt: Pressure 18 g Scavenge 1.6 g

Test Oil Performance

Test Time, hr	Vis, cs at 210°F	% Vis Increase at 210°F	Vis, cs at 100°F
0	25.69	--	286.9
4	27.56	7.2	322.6
8	28.34	10.3	328.6
11.6*	29.16	13.5	343.5

Rig No. 2, with 5 metal specimens in test oil sump

Sump temp, °F	650
Oil-in temp, °F	632
Bearing temp, °F	700
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Deposit formation necessitated test termination

TABLE 114. SUMMARY DATA ON ATL-401, BEARING TEST NO. 70

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	2	2	4
Heater Mount (F)	22.5	3	67.5
Heater Mount (R)	76	3	228
Seal Plate	0	1	0
Test Bearing	8.2	5	41
			340.5

Overall Rating 340.5/6 = 56.8

Not included in official rating: Sump-wall 100% clean
bottom 100% L Varnish

Oil consumption rate: 79 ml/hr

Total accumulated filter wt: Pressure 0.9 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.30	--	5.13	0.10
4	28.50	8.4	5.42	0.53
8	32.53	23.7	5.78	1.04
12	34.96	33.0	6.25	1.14
16	37.67	43.3	6.58	1.28
20	38.62	46.9	6.69	1.54
24	41.49	57.8	6.99	1.64
28	42.93	63.3	7.02	1.68
32	46.38	76.4	7.60	1.91
36	47.54	80.8	7.72	2.00
40	49.92	89.9	7.98	2.24
44*	52.25	98.7	8.30	2.45

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	417
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test terminated at 44 hr due to viscosity increase.

TABLE 115. SUMMARY DATA ON ATL-401, BEARING TEST NO. 58

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	0	2	0
Heater Mount (F)	60	3	180
Heater Mount (R)	40	3	120
Seal Plate	30	1	30
Test Bearing	9.2	5	46
			376

Overall Rating: 376/6 = 62.7

Not included in official rating: Sump-wall 100% clean
bottom 10% L sludge, 90% clean

Oil consumption rate: 73 ml/hr

Total accumulated filter wt: Pressure 1.0 g Scavenge 1.2 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.30	--	5.13	0.10
4	28.41	8.0	5.42	0.61
8	31.59	20.1	5.78	0.88
12	33.83	28.6	6.11	1.07
16	36.41	38.4	6.45	1.34
20	36.97	40.6	6.57	1.34
24	40.41	53.7	6.92	1.34
28	42.93	63.2	7.19	1.39
32	45.32	72.3	7.53	1.58
36	47.88	82.1	7.84	1.74
40	49.54	88.4	8.08	1.80
44*	52.67	100.3	8.39	2.04

Rig No. 1, with 7-metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	417
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test terminated after 44 hr due to viscosity increase.

TABLE 116. SUMMARY DATA ON ATL-401, BEARING TEST NO. 78

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	6	2	12
Heater Mount (F)	40.5	3	121.5
Heater Mount (R)	66.5	3	199.5
Seal Plate	0	1	0
Test Bearing	14.5	5	72.5
			405.5

Overall Rating: 405.5/6 = 67.6

Not included in official rating: Sump - wall 100% clean
bottom 100% clean

Oil consumption rate: 116 ml/hr

Total accumulated filter wt: Pressure 0.8 g Scavenge 1.0 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.30	-	5.13	0.10
4	29.59	12.5	5.57	0.62
8	34.28	30.3	6.19	1.03
12	38.79	47.5	6.68	1.21
16	41.72	58.6	7.09	1.36
20	44.11	67.7	7.39	1.72
24	48.56	84.6	7.81	2.02
28*	52.64	100	8.30	2.34
32	32.70	24.3	5.94	0.85
36	35.09	33.4	6.30	1.16
40	38.50	46.4	6.71	1.23
44	41.75	58.7	7.02	1.35
48	44.96	71.0	7.39	1.67

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil-in temp, °F	416
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	1.0

* Test oil changed at 28 hr due to viscosity increase.

TABLE 117. SUMMARY DATA ON ATL-401, BEARING TEST NO. 56

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	12	2	24
Heater Mount (F)	17.5	3	52.5
Heater Mount (R)	46.5	3	139.5
Seal Plate	10	1	10
Test Bearing	7	5	35
			261

Overall Rating: 261/6 = 43.5

Not included in official rating: Sump -wall 5% L varnish. 95% clean
bottom 100% clean

Oil consumption rate: 120 ml/hr

Total accumulated filter wt: Pressure 0.8 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.30	--	5.13	0.10
4	29.06	10.5	5.46	0.37
8	33.30	26.6	6.00	0.76
12	37.76	43.6	6.37	0.86
16	41.96	59.5	7.06	0.95
20	45.23	72.0	7.38	0.96
24	49.20	87.1	8.02	1.19
28*	27.23	3.5	5.24	0.20
32	32.05	21.7	5.83	0.67
36	36.19	37.6	6.37	0.77
40	39.31	49.5	6.89	0.94
44	44.94	70.9	7.34	1.04
48	50.05	90.3	8.35	1.14

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	475
Oil-in temp, °F	464
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 27 hr due to viscosity increase.

TABLE 118. SUMMARY DATA ON ATL-401, BEARING TEST NO. 73

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	2	2	4
Heater Mount (F)	18	3	54
Heater Mount (R)	47.5	3	142.5
Seal Plate	0	1	0
Test Bearing	14.4	5	72
			272.5

Overall Rating: 272.5/6 = 45.4

Not included in official rating: Sump - wall 10% H varnish, 90% clean
bottom 100% clean

Oil consumption rate: 196 ml/hr

Total accumulated filter wt: Pressure 0.9 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.30	-	5.13	0.10
4	29.71	13.0	5.55	0.72
8	36.73	39.7	6.43	0.80
12	43.94	67.1	7.34	0.86
16	52.59	99.9	8.41	1.01
20*	55.52	111.0	8.52	1.12
24	32.20	22.4	5.84	0.57
28	37.94	43.1	6.57	0.71
32	45.04	71.3	7.43	0.89
36	49.83	89.5	8.02	1.04
40*	26.45	0.6	5.24	0.19
44	33.90	28.9	6.07	0.68
48	39.46	50.0	6.75	0.73

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	500
Oil in temp, °F	488
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

* Test oil changed at 20 and 39.5 hr due to viscosity increase

TABLE 119. SUMMARY DATA ON ATL-401, BEARING TEST NO. 71

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	18	2	36
Heater Mount (F)	17.5	3	52.5
Heater Mount (R)	55	3	165
Seal Plate	0	1	0
Test Bearing	17.4	5	87
			340.5

Overall Rating: 340.5/6 = 56.8

Not included in official rating: Sump - wall 80% H varnish, 20% L varnish
bottom 50% L sludge, 50% clean

Oil consumption rate: 283 ml/hr

Total accumulated filter wt: Pressure 1.2 g Scavenge 1.5 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	26.30	--	5.13	0.10
4	30.32	15.3	5.57	0.81
8	43.43	65.1	7.16	1.01
12*	28.80	9.5	5.32	0.26
16	39.18	49.0	6.73	0.98
20	46.25	75.9	7.57	2.12
24*	53.42	103.1	8.42	3.22
28	35.98	36.8	6.34	0.75
32	47.13	79.2	7.69	0.95
36*	54.03	105.4	8.46	1.20
40	36.50	38.8	6.37	0.75
44	47.01	78.7	7.61	0.96
47**	55.02	109.2	8.57	1.00

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	514
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 11, 24, and 36 hr due to viscosity increase.

**Test terminated at 47 hr due to viscosity increase.

TABLE 120. SUMMARY DATA ON ATL-402, BEARING TEST NO. 67

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	16.5	2	33
Heater Mount (F)	0	3	0
Heater Mount (R)	38.5	3	115.5
Seal Plate	0	1	0
Test Bearing	17.1	5	85.5
			234

Overall Rating: 234/6 = 39

Not included in official rating: Sump - wall 10% L varnish, 90% clean
bottom 100% clean

Oil consumption rate: 132 ml/hr

Total accumulated filter wt: Pressure 0.7 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	46.84	--	8.25	0.12
4	49.71	6.1	8.27	0.42
8	56.40	20.4	8.98	0.86
12	63.46	35.5	9.57	1.12
16	71.47	52.6	10.67	1.39
20	72.86	55.6	10.97	1.39
24	85.83	83.2	12.20	1.50
28*	49.44	5.6	8.49	0.30
32	53.09	13.3	8.68	0.68
36	57.53	22.8	9.17	0.84
40	66.72	42.4	10.15	1.18
44	74.79	59.7	11.09	1.28
48	86.28	84.2	12.15	1.48

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	500
Oil-in temp, °F	490
Bearing temp, °F	550
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 27.5 hr due to viscosity increase.

TABLE 121. SUMMARY DATA ON ATL-402, BEARING TEST NO. 68

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	0	1	0
Spacer and Nut	36	2	72
Heater Mount (F)	15.5	3	46.5
Heater Mount (R)	59	3	177
Seal Plate	0	1	0
Test Bearing	65.5	5	327.5
			623

Overall Rating: 623/6 = 103.8

Not included in official rating: Sump-wall 10% M varnish, 90% clean
bottom 100% clean

Oil consumption rate: 172 ml/hr

Total accumulated filter wt: Pressure 0.8 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	46.84	--	8.25	0.12
4	48.97	4.5	8.25	0.42
8	59.19	26.4	9.27	0.90
12	69.31	48.0	10.43	1.05
16	83.07	77.3	11.91	1.21
20*	94.03	101	13.01	1.37
24	51.90	10.8	8.05	0.60
28	61.18	30.6	9.54	0.88
32	67.68	44.5	10.27	0.98
36	80.40	71.6	11.62	1.30
40*	47.78	2.0	8.25	0.30
44	55.42	18.3	8.87	0.77
48	62.66	33.8	9.66	0.91

Rig No. 1, with 5-metal specimens in test oil sump

Sump temp, °F	525
Oil-in temp, °F	512
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump	0

*Test oil change at 20.5 and 39 hr due to viscosity increase.

TABLE 122. SUMMARY DATA ON ATL-403, BEARING TEST NO. 69

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	12	1	12
Spacer and Nut	65.5	2	131
Heater Mount (F)	56	3	168
Heater Mount (R)	66.5	3	199.5
Seal Plate	12.5	1	12.5
Test Bearing	34.5	5	172.5
			695.5

Overall Rating: 695.5/6 = 115.9

Not included in official rating: Sump - wall 100% L smooth carbon
bottom 100% H sludge

Oil consumption rate: 209 ml/hr

Total accumulated filter wt: Pressure 3.9 g Scavenge 1.3 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	27.82	--	5.18	0.29
4	30.66	10.2	5.60	0.31
8	36.59	31.5	6.29	0.58
12	43.00	54.6	7.16	0.72
16*	54.45	95.7	8.69	1.01
20	33.30	19.7	5.86	0.39
27	38.33	37.8	6.52	0.45
28	43.01	54.6	7.15	0.83
32*	57.21	105.6	7.89	0.96
36	32.65	17.4	5.84	0.35
40	36.99	33.0	6.09	0.54
44	40.07	44.0	6.76	0.58
48	43.43	56.1	7.24	0.72

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	500
Oil-in temp, °F	488
Bearing temp, °F	550
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

*Test oil changed at 16 and 32 hr due to viscosity increase.

TABLE 123. SUMMARY DATA ON ATL-405, BEARING TEST NO. 75

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	6	1	6
Spacer and Nut	30	2	60
Heater Mount (F)	67.5	3	202.5
Heater Mount (R)	49.5	3	148.5
Seal Piate	3	1	3
Test Bearing	21.6	5	108
			528

Overall Rating: 528/6 = 88

Not included in official rating: Sump - wall 100% M sludge
bottom 100% M sludge

Oil consumption rate: 58 ml/hr

Total accumulated filter wt: Pressure 1.9 g Scavenge 1.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	34.45	-	6.31	0.09
4	34.31	-	6.26	0.12
8	36.07	4.7	6.42	0.18
12	36.93	7.2	6.46	0.26
16	35.95	4.4	6.42	0.37
20	36.82	6.9	6.46	0.49
24	38.70	12.3	6.58	0.90
28	42.31	22.8	6.91	1.39
32	45.21	31.2	7.25	1.68
36	47.83	38.8	7.52	2.23
40	51.48	49.4	7.93	2.75
44	54.67	58.7	8.32	2.97
48	58.54	69.9	8.65	3.27

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil in temp, °F	415
Bearing temp, °F	500
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

TABLE 124. SUMMARY DATA ON ATL-405, BEARING TEST NO. 74

Demerit Ratings

Item	Rating	Factor	Demerits
End Cover	44	1	44
Spacer and Nut	66	2	132
Heater Mount (F)	84	3	252
Heater Mount (R)	90.5	3	271.5
Seal Plate	48	1	48
Test Bearing	50.3	5	251.5
			999

Overall Rating: 999/6 = 166.5

Not included in official rating: Sump - wall 100% M sludge
bottom 100% M sludge

Oil consumption rate: 76 ml/hr

Total accumulated filter wt: Pressure 1.7 g Scavenge 2.1 g

Test Oil Performance

Test Time, hr	Vis, cs at 100°F	% Vis Increase at 100°F	Vis, cs at 210°F	Neut. No., mg KOH/g
0	34.45	-	6.31	0.09
4	34.96	1.5	6.29	0.34
8	36.47	5.9	6.36	0.50
12	36.84	7.0	6.40	0.57
16	39.44	14.5	6.64	1.18
20	42.02	22.0	6.91	1.76
24	45.98	33.5	7.32	2.50
28	49.57	43.9	7.77	2.77
32	53.52	55.4	8.08	3.04
36	55.96	62.4	8.42	3.30
40	60.01	74.2	8.89	3.75
44	65.57	90.3	9.50	4.08
46*	69.48	101.7	10.0	4.42

Rig No. 2, with 5-metal specimens in test oil sump

Sump temp, °F	425
Oil in temp, °F	417
Bearing temp, °F	575
Air flow to bearing machine, cfm	0.35
Air flow to test oil sump, cfm	0

* Test terminated at 46.33 hr due to viscosity increase